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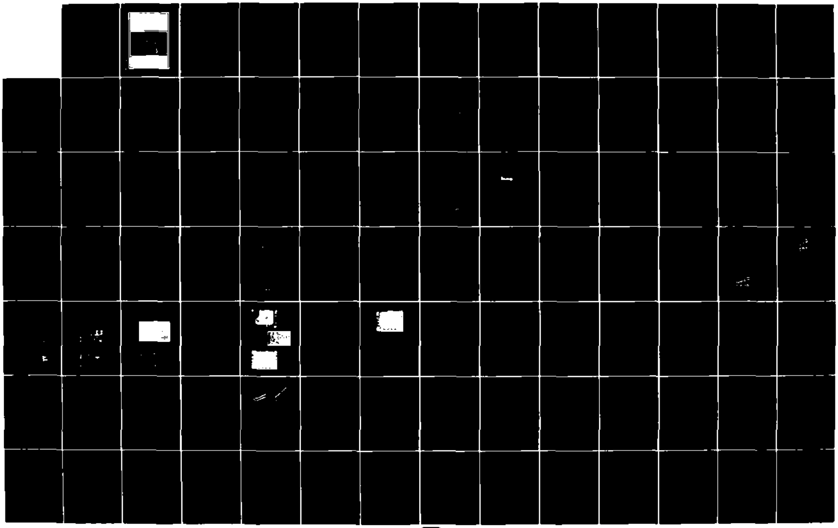

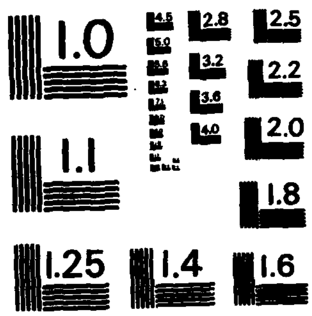

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Air Traffic Control in Face of Users' Demand and Economy Constraints

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NORTH ATLANTIC TREATY ORGANIZATION

ADVISORY GROUP FOR AEROSPACE RESEARCH AND DEVELOPMENT

(ORGANISATION DU TRAITE DE L'ATLANTIQUE NORD)

Conference Proceedings No.340

AIR TRAFFIC CONTROL IN FACE OF USERS' DEMAND AND ECONOMY CONSTRAINTS

This volume contains the papers presented at a Special Session held at the request of the Portuguese Authorities and sponsored by the Guidance and Control Panel of AGARD, 15 October 1982, Lisbon, Portugal.

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- Improving the co-operation among member nations in aerospace research and development;
- Providing scientific and technical advice and assistance to the North Atlantic Military Committee in the field of aerospace research and development;
- Rendering scientific and technical assistance, as requested, to other NATO bodies and to member nations in connection with research and development problems in the aerospace field;
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PREFACE

Before the 1973 crisis, safe expedition of traffic was certainly the essential concern of both the users and the Air Traffic Control Authorities. The operators aimed generally to fly close to maximum allowable speed, the consumption incidence on the operating cost remaining within reasonable limits. In fact, the price of fuel was kept practically constant from 1900 to 1973; in actual terms it even decreased over extended periods. Then the tide turned: in less than ten years, fuel prices have increased tenfold. Now that fuel has become the highest "single item" (at least 50 percent) in air transport operating cost, this has had a direct influence on the policies and economy of aviation resulting in the operations criteria being revised accordingly.

On all sides, appreciable efforts are being made or requested to attenuate the impact of the escalation of fuel prices on operating costs. The present situation renders critical the airlines' economy and even threatens their existence. Given that the military allocations are limited, the question of how airspace should be shared can be a crucial subject during discussions of the civil/military coordination aspects.

From a different point of view, automation and/or supporting techniques offer broad scope for the consideration of concepts hardly conceivable some twenty years ago. From avionics, flight mechanics, guidance and control to data processing and communications developments, it is certain that advanced technology is available today to enable an entire flight to be conducted in a completely automatic mode. At the same time some small aircraft will proceed with minimum onboard equipment in accordance with visual flight rules. Between these two extremes, the existing fleet operates to rules specified by ground-based authorities (control, environment, . . .).

Faced with a host of contradictory requirements, offered a wide range of new techniques and automated aids, can or should Air Traffic Control revise its attitude, rules and current conduct of the control of aircraft? The answer is a resounding "YES". Critical surveys of the various sources of fuel savings involving manufacturers, operators, air traffic authorities etc. and ranging from day-to-day maintenance to the design of new powerplants, clearly indicate that potential contributions of Air Traffic Control to the economy of air transportation are considerable; this is probably the most substantial contribution which can and will be made in the next ten years.

In Western Europe, more specifically in the region covered by the EUROCONTROL Route Charges System, the excess cost of flights (actual as against ideal) is estimated to be at least equivalent to two million tons of fuel per year, one million for the excess route lengths and one million for the use of non-optimum trajectories in the present air-route network.

It is believed, and in some cases established, that the expected benefits which would result from the measures proposed would easily compensate for the investment required. The Air Traffic Authorities conscious of these facts have taken local measures to ease the situation. National and International Administrations have published exhaustive lists of possible contributions to the reduction of fuel consumption and precise recommendations have reached international assemblies. However, the process of reviewing control standards and procedures is progressing at an extremely slow pace, indeed, the conception and acceptance of advanced aids requires the build-up of a high level of confidence both on the ground and in the air. In the United States, the Federal Aviation Administration has defined a plan to modernise the present system while providing a framework for the future National Airspace System. This appears to be the first time that Air Traffic Control is, as a whole, being considered as a large-scale system, i.e. the control operation resulting from the objectives, needs and multiple functions which may be developed using modern science, engineering and technology.

The Guidance and Control Panel of AGARD is closely associated with the developments made or applicable in the field of air traffic (see for instance "Air Traffic Control Systems" CP-105, 1972; "Plans and Developments for Air Traffic Systems" CP-188, 1975; "A review of Modern Air Traffic Control", Vols. 1 and 2, AG-209, 1975, "Air Traffic Management, Civil/Military Systems and Technologies" CP-273, 1979). At this stage, it was reasonable to attempt to produce a state-of-the-art review, inviting the Military and the Civil Operators, the Air Traffic Control Authorities, the Research Institutions and Specialised Consultants to express their concerns and requirements, to show their contributions or expose their plans and, above all, to exchange objective views on a subject affecting all concerned with aviation in general and air transport in particular.

The opportunity for such an event was offered by the initiative of the Portuguese National Delegation to AGARD, inviting the Guidance and Control Panel to organise a special one-day session to review the present situation in face of the users' requirements, economic constraints and developments in technology. The materials available in the NATO countries could readily be brought to an open forum thanks to the exceptional response of all Authorities and Institutions concerned.

We would like to express our sincere appreciation to all the Authors and Session Chairmen who agreed to share their knowledge and experience for the benefit of the whole community.

We are grateful to the Portuguese National Delegation to AGARD for suggesting and hosting this Conference. In particular, we would like to thank Eng. Antonio Alves-Vieira and his colleagues for the coordination of the meeting conducted in an efficient and most pleasant manner.

Dr André Benoît
Program Chairman
Guidance and Control Panel

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THE ZONE OF CONVERGENCE CONCEPT

SITUATION PRESENTE, ET BESOINS

par

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1. Voilà un beau thème de réflexion lancé comme un défi à la communauté internationale aéronautique. Mais ce défi est bien à la mesure des problèmes de circulation aérienne en Europe comme dans le reste du monde.

2. Malgré son développement spectaculaire, le transport aérien reste fragile, vulnérable et sensible aux moindres aléas. Il souffre tout à la fois, d'une sous capacité de l'ATC qui limite le volume de son trafic et de conditions d'exploitation qui le pénalisent en consommation de carburant et en temps de vol. Ces faiblesses qui réduisent le rendement économique du système ont été mises en évidence par le renchérissement du coût du carburant survenu dès 1973/74 et amplifiées par le 2ème choc pétrolier du 1979/1980.

   Le résultat est une diminution de la compétitivité du transport aérien et une menace sur son expansion.

3. De leur côté, les forces aériennes sont soumises à des contraintes opérationnelles extrêmement sévères. Les systèmes d'armes dont elles disposent, de plus en plus perfectionnés, s'accommodent mal des règles strictes de répartition de l'espace en plan et en niveau, qui, il n'y a pas longtemps encore, répondaient largement à leurs besoins.

4. Face à ces besoins, deux axes d'efforts sont à privilégier, l'un visant à une meillure utilisation de l'espace aérien, par les usagers civils et militaires, l'autre à une meillure gestion du trafic aérien.

5. Le premier objectif ne peut être résolu que par une approche nouvelle du délicat problème de la répartition de l'espace entre civils et militaires.

   Déjà une attitude favorable des autorités responsables dans les principaux états européens permet d'obtenir un plus grand nombre de routes directes pour les compagnies tout en répondant mieux aux besoins légitimes des militaires. Il faudra probablement aller plus loin, en modifiant les règles d'utilisation de l'espace aérien pour le plus grand bénéfice, tout à la fois, des civils et des militaires.

   Dans ce domaine, il existe un large champ d'action qui mérite d'être exploré pour le plus grand bien de la communauté aéronautique.

6. Mais il ne suffit pas d'adapter l'utilisation des espaces aux besoins de l'ensemble des usagers. Faut-il encore viser à mieux gérer le trafic aérien et là, j'addresserai un plaidoyer en faveur de méthodes de contrôle permettant de satisfaire les besoins propres de chaque usager en fonction de la situation réelle de l'ensemble du trafic pour retenir, chaque fois que possible la route la plus directe, le niveau de vol le plus proche du niveau de vol optimal et en laissant le choix des vitesses à la discrétion du pilote.

   Les compagnies investissent dans des systèmes de préparation de vol et de gestion de suivi de vol de plus en plus perfectionnés pour réduire leur consommation de carburant. Elles attendent du contrôle des méthodes de gestion de trafic, moins simplificatrices que celles encore en usage aujourd'hui et plus en accord avec les réalités économiques auxquelles elles sont confrontées.

7. En définitive quels sont les points qui, d'une façon ou d'une autre, méritent toute notre attention. Certainement, en premier lieu, une réflexion commune entre civils et militaires qui devrait déboucher sur des actions visant à mieux faire correspondre les règles d'utilisation de l'espace aux besoins de l'ensemble des usagers. En deuxième lieu, une meilleure utilisation des moyens déjà existants pour accroître les performances du système ATC, tant en matière de capacité (aéroportuaire, espace aérien) qu'en matière de coût (meilleur ajustement de l'infrastructure aux besoins réels des usagers) et enfin un développement mesuré des différents composants du système ATC en veillant, à chaque pas, que l'efficacité recherchée ne se fasse pas au détriment de l'économie du transport aérien par le biais des redevances perçues auprès des compagnies.

   Je suis convaincu que cette session contribuera à faire avancer nos réflexions dans l'un au moins de ces domaines. Ce mérite en reviendra aux organisateurs de ce symposium, que je tiens avant tout à remercier, et aux conférenciers, tant civils que militaires, qui vont en assurer le succès.

PRESENT SITUATION AND REQUIREMENTS

1. This topic gives food for thought and is a challenge to the international aeronautical community. This challenge is indeed proportionate to air traffic problems in Europe as well as all over the world.

2. Despite its spectacular development, air transport remains vulnerable and susceptible to the slightest adverse events. It suffers from the insufficient capacity of the ATC which sets limits to the volume of air traffic, as well as from the operating conditions which entail penalties with regard to fuel consumption and flying time. Such shortcomings, which reduce the economical efficiency of the system, were shown up by the rise in fuel cost which took place as early as 1973/74 and amplified by the second fuel crisis in 1979/1980.

   As a result, the competitiveness of air transport is reduced and its extension threatened.

3. In addition, the air forces are subject to extremely severe operational constraints. Their increasingly sophisticated weapon systems do not comply easily with strict rules of space distribution either on the horizontal or vertical planes, although these rules were still suited to their needs until recently.

4. To meet these requirements, efforts should be directed along two lines:
   1) better air space utilization by civilian and military users;
   2) better air traffic management.

5. The first objective can only be reached through a new approach to the difficult problem of space distribution among civilian and military users.

   Already, thanks to the favourable attitude of the authorities concerned in the main European states, a large number of direct air routes can be obtained for airlines while the legitimate needs of the military are more suitably met. However, one should probably pursue this effort by modifying the rules which govern the use of the air space, for the benefit of both civilian and military users.

   Along this line, there is a wide field of action which deserves to be explored for the benefit of the aeronautical community.

6. However, adapting the use of spaces to the needs of the overall users is not a sufficient measure. In addition, one should strive for a better management of air traffic. In this regard, I wish to advocate control methods which make it possible to meet the specific needs of each user based on the actual overall traffic situation and to select, whenever possible, the most direct air route and the flight level the closest to the optimum, while leaving the choice of speeds to the pilot.

   To reduce their fuel consumption, airlines invest money in increasingly sophisticated flight planning methods and flight monitoring systems. They expect the ATC to provide them with air traffic management methods containing more information than is supplied today and better suited to the economical realities with which they are confronted.

7. In fact, what are the points which claim our attention in some way or other? Firstly, by all means, the problems should be studied jointly by civilian and military users with a view to defining actions which would ensure that the rules of space utilization are suited to meet with the needs of all the users. Secondly, the means already existing should be used more efficiently to increase the performance of the ATC system as regards both capacity (airports, air space) and cost (better adaptation of the infrastructure to the genuine needs of the users), and lastly an integrated development of the various ATC system components taking care, at each stage, that the efficiency sought is not achieved to the prejudice of the air transport economy on account of the fees charged to the airlines.

   I am convinced that this meeting will contribute to stimulate our thinking in at least one of these fields. We shall be indebted for this to the organizers of this Symposium, whom I wish to thank, and to the authors of papers, both civilian and military, who will ensure the success of the meeting.

A UK NATS VIEW OF THE AIR TRAFFIC MANAGEMENT REQUIREMENTS IN THE NEXT DECADE

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ANGLETERRE

"This paper reviews the main categories of user demand in United Kingdom airspace at present and the Air Traffic Management infrastructure currently provided.

It describes aspects of NATS plans for improvement and modernisation of ATC facilities and the relationship of these plans to improved economy and fuel conservation is outlined. The main focus of these plans is related to development of ATC capability in the London and South East England area, therefore the re-development of the London Air Traffic Control Centre is described in the context of the theme of the Special Session.

The relationship applicable to the United Kingdom between financial policy, implementation plans and the cost to system users is discussed in view of the constraints it places on the ability of the ATC system to meet commercial demand for the most economic service."

I hope the theme of my talk will prove to be a worthwhile start to your Seminar on "Air Traffic Control in Face of Users Demand and Economy Constraints". As time is short I will have to ignore the historical factors which have influenced the Air Traffic Management organisation and methods employed in the United Kingdom Airspace and begin with a brief review of the current situation.

The airspace users can be divided into three arbitrary categories - military, civil and recreational. These are not watertight compartments; there are areas of overlap, and fringe activities, but the three classes serve to identify the main areas of common interest and mutual conflict.

First I will address civil commercial operations. The public transport operator is essentially concerned with safety, reliability and economy. In many cases his activities are predictable and planned in advance. He requires his flight to be injected, at the time of his choice, into a system permitting him to fly the most economic profile direct to its destination and land there without delay, whilst being protected absolutely from the danger of collision with other traffic. He needs a comprehensive network of accurate navigational and approach aids to allow him to provide his services in all weather. The system should allow him to cross the boundaries of national airspace without discontinuity of service or marked disparity in traffic capacity. He is accustomed to and expects a high standard of positive control from the ground, as the operation of a reliable public transport service depends upon a close working relationship between the operator and the ATC system.

The second category of user is the military, including in our case not only the Royal Air Force but the Navy, the Army, the test and development organisation, the USAF and the other allied air forces which use our airspace for training from time to time.

With the exception of the transport force and communications squadrons (whose airspace requirements are more like those of commercial operators) the vast majority of military peacetime flying is training, at various levels of experience; training aircrew for a war which would entail flying in a hostile environment where, at best, there would be only limited advice from the ground and at worst the local airspace management people would be trying to eliminate them from the scene altogether.

Thus in military flying the emphasis is on self-reliance rather than ground-based navigational aids; on the freedom of manoeuvre rather than close control. It is only fair to add that various military authorities differ in their assessment of the extent to which effective control from the ground could be accomplished in a future war; hence the emphasis placed on independent operation in the training programme. However, this is a variation in degree only, and a military pilot must be trained to operate effectively without help from the ground.

His requirements for air traffic services are very different, comprising terminal control at airfields, an orderly system for despatch and recovery around major bases in poor weather, and an emergency organisation. A flight information service is sometimes useful as are traffic information and collision avoidance service during transit between his base and weapon ranges or low flying areas. When military aircraft request an air traffic service it is often merely to cross or circumnavigate an artificial airspace obstruction created by the ATC system in the first place. Nevertheless, military activities themselves create the need for protective airspace around dangerous areas, such as weapon ranges, with corresponding effects on other airspace users.

By convention, all flying that is not public transport or military is listed as "General Aviation". This is not the sort of definition that lends itself to easy analysis of user requirements as it embraces everything from hang-gliding to executive jets and includes both commercial and recreational activity. However we can discount those operatio[illegible] at the top [illegible] of the scale since they seek a similar service to public transport operators. The wide [illegible] [illegible] is broadly concerned with off-route flying, generally of a localised nature. There are special[illegible] [illegible] operations such as crop-spraying and off-shore helicopter operations, which are particularly vulner[illegible] [illegible] [illegible] protection from other traffic, and there are air-taxi operators who need to fly between major airports and small strips. Then there is the broad body of

recreational flying which is the third category NATS have to serve. This flying comes in many shapes and sizes and the traditional club, training, local pleasure and private activity at bigger aerodromes is only part of the scene. The gliding fraternity (hang-and conventional) want the minimum of restriction and interference but like their flying sites and soaring locations protected from intrusion. Flying clubs and private owners may like air traffic control around their own aerodromes, they do not require a service elsewhere but do want sufficient navigational aids around the country. They are sometimes not averse to taking an advisory or collision avoidance service but some who do not carry radio are inconvenienced by an airspace restriction which requires communication with the ground.

Recreational flying shares with military aviation a large measure of independence from air traffic services away from the aerodrome. However, since it is not subject to the same centralised direction as military flying, it is less amenable to the imposition of an air traffic service if this is necessary for safety and it can conflict with military interests where airspace restrictions need to be imposed for military purposes.

I will now describe our present airspace structure with which NATS attempts to meet the needs of our 3 classes of airspace users.

Starting with public transport, our route structure is largely determined by geographical facts; internal routes must run from London to the major provincial centres. Moreover since the United Kingdom lies on the great circle route between Europe and North America, our routes must cater for the majority of Europe's transatlantic traffic.

In accordance with ICAO practices, we protect the major airports and main routes with controlled airspace. By the application of an additional rule we make IFR mandatory within most of the controlled airspace so that all traffic is subject to control. This we consider is highly desirable in order to avoid a mix of controlled IFR and uncontrolled VFR traffic. The price we pay for this is that an airway becomes more of a hurdle for non-airways traffic, thus the creation of an airway is a major step invariably resisted by the military and some factions of General Aviation.

Where traffic intensity does not justify controlled airspace we institute Advisory Routes which allow for the separation of participating aircraft but no formal protection from other traffic. Under ICAO definition the ADR is seen as a temporary measure but we tend to treat them as a permanent compromise and they are generally treated with respect by other users.

In the open FIR the freedom for all sorts of traffic to proceed at will results in a requirement for a voluntary separation service, generally provided by military controllers. This takes the form of a Radar Advisory Service, provided on request within cover from NATS units and the Lower Airspace Radar Advisory Service which fills in much of the airspace below FL 95 and is provided from military airfields and one civil airport. These services do require an aircraft to maintain a given heading and level and are thus only suitable for off-route traffic in transit. We have recently added a more relaxed Traffic Information Service for those who wish to manoeuvre freely but still like information on what is going on around them.

Above FL 245 a totally different arrangement exists. Most of this airspace is not "controlled" in the formal sense but is covered by a Special Rule which requires all civil aircraft to be under an air traffic service, while the same airspace is divided into Mandatory Radar Service Areas which cause military aircraft to take a service from a military controller. The airways are projected upwards in the form of Upper Routes and operating procedures ensure that civil and military controllers coordinate traffic movements. The advantage of this arrangement is that although civil traffic may often be confined to the Upper Routes, there is no reason why it cannot take a more direct track if off-route conditions permit; it can remain under the same controller and suffers no loss of protection.

There is of course a requirement for military aircraft to carry out free manoeuvres in the Upper Airspace and we designate quite large Military Training Areas covering such activity. Within certain hours access has to be denied to controlled traffic.

Having briefly covered the factors which have influenced the characteristics of our current airspace design I must now consider its ability to meet the traffic demand. The last twenty years have seen a three-fold increase in the volume of en route traffic and a doubling of the altitude at which most of it wishes to fly. Similarly air transport movements at the London airports has grown at the same rate. This growth has created a situation in which a large number of operators wish to use the same runways or fly the same routes at one time. The combined effects of curfew hours and passenger preference, especially where long haul and internal flights are competing for the same facilities, create a far greater degree of conflict and delay than would arise in a random distribution.

There is clearly a limit to the number of direct routes that can be established even before we come to consider the needs of the off-route operators. At first glance one might imagine that the current network of routes in the Central European area would cater for all needs, yet there are still frequent complaints about dog-legging and indirect routeing. The difficulty is that the number of crossing points increases with proliferation of routes and every crossing point represents a potential traffic conflict which needs to be monitored. There has to be a balance between the ideal of direct routes from everywhere to everywhere and the control centre's capacity, with current skills and equipments to monitor a finite number of crossing points.

Traffic demand still exceeds system capacity at times and looking back over the last 10 years one extremely adverse factor has been the replacement of turbo-propellor traffic which was content to cruise at up to 20,000 ft by short and medium haul jets with a strong preference for FL 270 to 330. Above FL 290 2000ft vertical separation must be provided so limiting the cruising levels available. Under conditions of route saturation some sort of flow control is inevitable and at such times the airliner that can comfortably accept a wide range of cruising levels is worth its weight in gold.

In the medium term there is great scope for improving overall route capacity by the elimination of bottlenecks which have an effect throughout the European system. In the longer term any absolute increase must stem from either a reduction in separation standards or an expansion of the physical dimensions of the en-route system. However a reduction in separation standards is a very long process which can only be introduced when the preponderance of traffic has proved its ability to meet more demanding tolerances. An expansion of the route system runs counter to the interests of off-route operators - military and civil - and can be considered only as a last resort.

During the period of growth of en-route traffic the centre of gravity of military training has swung to low level, and despite a serious reduction in the numbers of military aircraft based in this country, their performance and capability for all-weather operations continues to place great demands on available airspace. General Aviation has increased by at least 300% and has diversified almost out of recognition.

Airspace management has changed to meet changing circumstances and this has tended to be an evolutionary process. Inevitably there will be further shifts in the balance of requirements and there will be overall traffic growth but perhaps not at the rate we have experienced in the past.

Clearly the application of airspace management and design policies must be accompanied by the provision of compatible technical facilities to meet the demand for which the airspace structure has been designed.

During the same 20 year period the Air Traffic Services facilities have developed to meet the increasing demand and changing user requirements and now rely almost entirely on the use of radar to supply the basic surveillance information needed by ATC and to permit the use of smaller separation standards to expedite the traffic flow.

The introduction of Secondary Radar has enabled the aircraft discrete identity and height to be used on improved radar displays to ease the controllers task and improve his capacity. In the United Kingdom our Air Traffic Services for en-route flights are mostly concentrated at the London ATCC at West Drayton and at the Scottish ATCC at Prestwick. The latter centre also contains the Shanwick Oceanic Control Centre responsible for the eastern half of the North Atlantic adjacent to Europe. At each of these units there is an increasing use of automation to provide better display systems, to improve the speed and accuracy of coordination of flight movements by automatic data transfer both internally and to adjacent centres in Europe, all this aimed at increasing the capacity and efficiency of the system.

In the past the provision of ATC facilities has largely been related to the ICAO objectives of Air Traffic Services, to facilitate a safe orderly and expeditious flow of traffic. During the years of growth the avoidance of delay has been one of the prime considerations in trying to meet the demands of the airspace users. More recently two important factors have assumed much greater influence, firstly the political decision that the industry should bear the costs of the infrastructure provided for its use, both at airports and en-route, and secondly the shortage and high cost of fuel.

These fuel costs resulted in demands for ATC systems to use methods which reduce the amount of fuel used in flight by providing the most efficient flight profile from departure to arrival and this infers the elimination of in-flight holding. This however is accompanied by a resistance to procedures such as scheduling and flow control which affect the freedom of a user to plan his flight when he wishes. These methods are used to some extent in the United Kingdom where, at the busy London Airports, Scheduling Committees of users plan their operations according to the declared capacity of the runways to minimise delays induced by their own demand. Flow control procedures are enforced by ATC when demand is excessive due to abnormal factors within the United Kingdom airspace or due to the requirements of other National Air Traffic Management authorities.

As you will hear from Mr Barber in the next presentation much thought has been devoted to the potential for saving fuel and many individual possibilities have been identified. However a number of these require capital investment in ground and airborne facilities. The cost of providing and maintaining these must inevitably fall on the airspace user therefore it is important to be sure that the financial saving on fuel is not exceeded by the cost of saving it. This is particularly critical now when airlines are suffering badly from the world recession and we are finding it more difficult to find money to invest in new ATC facilities.

In the United Kingdom our ATC investment plan is subject to strict annual cash limits which cover expenditure to maintain our existing facilities and new equipment to provide a more advanced ATC system. The need to prove that the investment is cost effective is crucial except when safety considerations are clearly paramount.

Our latest Capital Investment Plan has been compiled to take the financial stringencies into account and I hope to illustrate its potential contribution to fuel saving over the next ten years. I will do this by describing the largest project now under way, the redevelopment of the London Air Traffic Control Centre.

The objectives of this project can be fairly simply summarised as follows; not necessarily in order of priority:

1. Modernisation of an obsolescent system

2. Centralisation of area Air Traffic Services at London ATCC

3. Maximum use of the IBM 9020D computer

4. A common data base for on-route and off-route services

5. Steady progression to more advanced ATC techniques based on data processing

6. Provision of more capacity for traffic demand

7. More efficient use of available airspace.

The system improvements we will provide are:-

1. Comprehensive use of the 9020D data base

2. An Electronic Data Display and Update System (EDDUS) - a sophisticated traffic display and automatic data transfer system

3. New radar sensors - primary and SSR with monopulse giving a more accurate surveillance system

4. An advanced Radar Data Processing System giving a mosaic radar picture

5. New ATC Furniture with modern input devices to the computer and communications systems

6. Modern 23 inch near vertical radar displays

7. New Radio Distribution equipment

8. New telephone system

9. Support Information and Retrieval System (SIRS)

10. Military Airfield Remote Entry Terminals (MARET)

11. Capability for rapid system reconfiguration.

The current Radar Replacement Programme is part of a plan to improve the quality of surveillance data to be used in the automation programme. The application of monopulse techniques which arises from our research into Mode S, enables us to overcome the more serious effects of track jitter, and garbling whilst improving the effective cover of our SSR equipment. Without requiring a new transponder fit in aircraft it will improve our radar system, probably as far as is practical until the introduction of Mode S stations can be shown to be cost-effective in UK airspace. Within the next few years the current programme will be extended to the Scottish FIR and will include, about 1985, a new radar site to provide better cover of the North Atlantic approaches.

Within the same timescale we expect to make similar improvements at the Scottish ATCC at Prestwick, a fairly modern domestic centre opened in 1978. There too, we are installing a flight data processing system at the Oceanic centre and expect this to be operational in the winter of 1984/85.

Turning to the aerodrome scene for a few moments, the ATC capacity is directly related to the runway movement rate which can be achieved in instrument conditions. Except at Heathrow and Gatwick we have no great problems in this respect. There is a Public Inquiry in progress to help determine whether Stansted should be developed as a major third London Airport. It is possible therefore that we will have to develop our facilities there and if so revise our ATC system in the London Terminal Area as a whole. This aspect is under active study at present and the need for a fuel-efficient operation is prominent in our minds.

We hope to replace our radar equipment at a number of aerodromes and provide a modest number of SSR processing systems where this is cost-effective. An ILS replacement programme is being undertaken to carry us through to the introduction of MLS when it is deployed internationally as the standard system.

Time does not allow me to cover all aspects of our Investment Plan but having used a few important examples I would like to conclude with a few thoughts on the combined effects of our airspace management policy and its supporting technical facilities.

We see little prospect of a major re-design of our airspace structure as it appears quite impracticable to cater for total freedom, maximum protection and minimum fuel costs for all airspace users.

However the centralisation of our Air Traffic Services supported by advancing automation and the creation of a sophisticated data base should enable us to make better use of airspace. In 1983 we intend to make the use of SSR mandatory above FL 100 and we may then be able to work towards a uniform airspace within which all traffic is under air traffic service, except within some Military Training Areas. These could be sectorised vertically and horizontally, opened and closed on demand, thus allowing some genuine "Airspace Sharing" and allowing direct routeing of controlled en-route traffic when the areas were not required for military use.

We see continuation of the current "airspace rationing" below FL 100, where airways will still be required for helicopter and STOL services and where it will still be possible for traffic to operate freely in uncontrolled airspace, if necessary without transponders or radio.

Control Zones and Terminal Areas will probably remain more or less the same size as at present, but completely reorganised internally to provide for optimum performance departures and metered arrivals, perhaps exploiting on-board flight management systems. Considerable development and investment in ATC automation will be essential, possibly associated with the deployment of Mode S and data link, but all this is unlikely to come to fruition or be cost-effective in the UK for another 15-20 years.

There will be no easy "no cost" solution to achieve absolute freedom of operation for all users of our relatively small airspace and it seems likely that, except for low-level flight, the best prospect lies in the development of automated techniques. These we believe will enable us to increase our system capacity to handle increased demand economically and safely. NATS is giving considerable support to research and development and Mr Barber will be giving more detail on the United Kingdom programme in the next presentation.

Clearly, NATS has a vested interest in the economic health of its customers and intends to give them every assistance in flying the shortest distance between "two dollar notes".

FUEL CONSERVATION AND ECONOMY CONSTRAINTS

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SUMMARY

Fuel conservation in civil aviation may be achieved by increasing the efficiency of the aircraft themselves, by operating the aircraft more efficiently, and by providing them with a more efficient air traffic environment. This paper discusses these three aspects briefly, and goes on to examine possible improvements in the air traffic management environment in more detail. Finally, attention is drawn to the Research and Development programme needed to achieve fuel conservation by improved air traffic management.

1 INTRODUCTION

There has been much appraisal and assessment in recent years of means by which fuel may be saved in civil aviation. Not only is it important to conserve a dwindling natural resource, but also fuel economy is crucial to the survival of many commercial airlines. In civil aviation, there is potential for fuel economy by increasing the efficiency of the aircraft themselves, of the way in which those aircraft are operated, and of the ATM environment in which they operate. In the UK a study team, known as the Air Traffic Management Fuel Conservation Working Group has been investigating this latter area in detail. The Group comprises representatives of the UK Civil Aviation Authority, the Government Research Establishments, the Airlines and the relevant sectors of Industry. This paper is based on the findings of that Working Group.

2 POTENTIAL FOR FUEL SAVING

The three aspects of civil aviation which offer potential for fuel economy are discussed briefly in the following paragraphs:

(a) <u>The aircraft (airframe, propulsion and avionics)</u>

The potential for improving the efficiency of aircraft has been estimated by many people and a summary of their results is given in Fig 1. From this it can be seen that compared with aircraft entering service in 1978, new aircraft types entering service in 1990 could be using 30% less fuel and for those by the year 2000, 50% less fuel.

(b) <u>The operation of aircraft (flight control, procedures, flight planning, maintenance, etc.)</u>

The fuel saving to be gained from the efficient operation of the aircraft itself depends upon the modus operandi of the individual operator.

As the cost of fuel is increasing faster than other flying time related costs, operating speeds for minimum cost have generally been reduced, and are now close to the minimum fuel/maximum range speeds. This has typically produced savings of some 2-3%. Safety remains the prime factor, but the increases in fuel price are making all airlines give more consideration to the fuel efficiency of the operation. This is through the use of climb, cruise and descent speeds related to actual aircraft weight, minimising time spent in high drag configurations by early flap retraction after take-off and with delayed flap and gear extension on approach to land etc.

The more efficient airlines have been using such techniques for many years, and their recent savings (approx 3%), primarily come from speed reductions.

Airlines that have practised more standardised procedures in the past at the expense of fuel efficiency can show savings of over 10% by adopting more flexible techniques.

(c) <u>The operating environment</u>

The fuel penalties resulting from the shortcomings in the operating environment can be estimated with a reasonable degree of confidence. The "ideal" standard against which the penalties have been derived assumes the aircraft flies the shortest route, achieves the optimum flight profile and has zero delay. Having established the penalties, it is a matter of judgment to decide the potential for fuel saving. Figures 2 and 3 show the estimated percentage fuel penalties and potential savings for operations in UK/Europe and across the North Atlantic. Detailed "conservative" overall estimates are given in Table 1. It is recognised that it would

not be possible in the "real" world to reduce the fuel penalties to zero and the results given in Figures 2 and 3 indicate what fuel savings might be achieved. It will be seen that the potential fuel savings are estimated at about 30% of the penalty in UK/Europe and about 40% over the North Atlantic.

The aim of this examination of the operating environment has been to attempt to quantify the potential for fuel saving by increasing the efficiency of ATM and to place the result into perspective against the other two areas where improved efficiency should be achieved. Comparing the three areas, then, by the turn of the century, the area associated with developing the aircraft has the greatest potential by at least an order of magnitude. Nevertheless, the potential savings due to improved ATM are significant, and warrant further attention.

3 THE ACHIEVEMENT OF FUEL CONSERVATION IN AIR TRAFFIC MANAGEMENT

It is suggested that there are four main means by which fuel saving might be achieved, namely:

i) Education

ii) Minimising constraints

iii) Research and Development

a) by ensuring that relevant present and planned R and D programmes take note of the need for fuel conservation, and

b) by initiating new R and D programmes aimed primarily at fuel conservation.

iv) Implementation

3.1 *Education*

The need to create an awareness, by education if necessary, in all those involved in the operation and control of civil aircraft of the need for fuel conservation is an important action. This does not only apply to aircrew and controllers, it should embrace for example designers of airfields, and of equipment, those responsible for Research and Development programmes etc. The means by which fuel can be conserved should be a key message in personnel training programmes.

3.2 Minimising constraints

There are many constraints and problems in ATC which militate against fuel conservation and the main ones which were identified are listed below against the three requirements for fuel conservation, but not necessarily in order of priority:

i) Shortest Route

Achievement of the shortest route is heavily penalised by constraints:

a)	aerodynamic:	aircraft have to take-off and land into wind
b)	noise:	preferential noise routes have to be flown
c)	airspace restrictions:	civil, military and general aviation have to share limited airspace
d)	restricted military areas:	military require certain airspace for specific purposes, e.g. weapon ranges
e)	location of airports and users:	historical position of airports and their users does not necessarily lend itself to minimum route length. For multi-airport cities, sectorisation would give the optimum utilisation
f)	location of navaids:	historical position of navaids may not allow shortest route
g)	implementation of navaids:	failure or delay in implementing regional plans
h)	International borders:	the need to interface routes with neighbouring countries may increase route mileage
i)	meteorological information:	inability to use the up-to-date meteorological situation prevents least time tracks being achieved across the North Atlantic

ii) Optimum Flight Profile

Constraints which prevent optimum profiles being achieved are:

a)	volume of movements:	individual aircraft cannot necessarily be given their optimum profile
b)	conflicting flight paths:	in busy airspace, e.g. TMA, conflicting requirements limit flight paths available

c) 2000ft separation above 29,000ft: increases height difference from preferred flight level

(iii) Zero Delay

Major constraints which cause delays are:

(a) the overriding requirement for safety and its associated separation standards

(b) the "planned" delays (scheduling) to maximise airport traffic flow in peak hours

(c) inability to adhere rigidly to overall traffic schedules.

Of these constraints some arise from fundamental or entrenched positions and are unlikely to be overcome. Others may only be reduced as a result of negotiation: some will respond to the implementation of technology; others as a result of undertaking R and D.

3.3 Research and Development

3.3.1 UK R and D Capability

It might be of interest to refer briefly to the relevant R and D facilities available within the UK. In addition to its internal capability, the UK Civil Aviation Authority has, at its disposal, teams and facilities at Government R and D establishments (RSRE, RAE and RAF/IAM), in Industry and in the Universities. Together, these comprise a comprehensive capability fully able to establish the criteria for effective fuel conservation in air transport. The facilities include:

(a) ground simulations of ATC systems for development and evaluation

(b) a BAe 1-11 aircraft installed with head-down electronic colour displays, navigation capability, up to 4D Navigation, a Flight Management System, and a variable auto-pilot

(c) the Advanced Flight Deck at BAe, and

(d) further facilities for the development of ground systems.

3.3.2 Research and Development Requirements

Against the three requirements for fuel conservation, and constraints given above, a detailed appraisal was undertaken, of the current action, whether involving R and D, or not, and what action might be initiated in the future. Forty-nine items of the current programme of Research and Development for Civil Aviation and National Air Traffic Services were identified as having varying degrees of relevance to the needs of fuel conservation and some of which could be re-directed to include fuel conservation as part of their aims.

In aiming to achieve the shortest route and/or the optimum flight profile, current studies using simulation and evaluation, will identify major contributions to fuel saving:

a) Flight Profile Studies to ensure that the future forecast traffic movement should flow expeditiously are being made. Because they are aimed at "efficient" and "cost-effective" flight profiles with minimum delay, they are by implication taking account of fuel conservation.

b) These studies are aimed at the short, medium and long term, i.e. well into the mid 1990's.

c) These studies cover movements across the North Atlantic, in UK airspace and in the interface with Europe.

d) In the considerations on the achievement of the least-time track across the North Atlantic and the Optimum flight profile in controlled airspace, the need for up-to-date meteorological data and its effective application is evident.

In addition to these studies other current R and D which should assist are:

a) the development of navigation, flight control and flight management systems

b) the identification and development of automated aids for ATC.

Feasibility studies which could establish the need for further R and D are:

a) improved meteorological reporting and forecasting and associated processing and application

b) reduced vertical separation about 29,000ft.

Turning now to minimising delays, a major part of the R and D which should assist in achieving this aim is already underway in the UK. There is work on:

a) obtaining improved knowledge of aircraft position

b) improved display of information both in the air and on the ground

c) data link development

d) improved input/output devices

e) relevant human factors investigations

f) conflict alert and avoidance

g) aids to facilitate all-weather operations.

The following additions to this proposed programme are:

a) establish the role of 4D Flight Management Systems in the basic ATC/aircraft control loop

b) undertake a definition of data link requirement for passing information between air and ground.

3.4 Implementation

Fuel conservation will only be achieved if the results of Research and Development are implemented. Equipment plans by the UK National Air Traffic Services (NATS), and new aircraft types due in service in the 1980's, both take advantage of the latest technology.

3.4.1 NATS Plan

You have already heard details of the NATS plan from the previous speaker. Many aspects of this programme for enhancing and increasing the capability of the Air Traffic System, are to cater for increased traffic demand as well as to expedite the traffic flow. These will have a favourable bearing on fuel conservation.

Areas of particular note are:

a) the progressive introduction of automated flight plan and radar data processing by utilising the IBM 9020 central computer complex, complemented by the development of a new Electronic Data Display and Update System (EDDUS) and Monopulse Secondary Radar Plot Extraction,

b) the development of or planning for flight data interchange links with European Centres and other communications improvements,

c) the installation of new primary and secondary radars utilising a co-mounted primary and secondary aerial system, remote control and monitoring facilities. These radars will take advantage of new techniques and in the case of secondary radar the SSR monopulse capability.

The NATS plans including the concentration of all civil and most military en-route services in the London FIR at the London Control Centre, making maximum use of the IBM 9020 computer complex and providing a common data base for all ATC operations, were seen as a sound foundation on which developments aimed at fuel conservation could be built.

In an ideal world many of the proposed ATC improvements should be available "tomorrow" but in reality rapid implementation is restricted by finance and resources.

3.4.2 Avionics/Ground Aids Standards

The progressive implementation of improved avionic systems into civil aircraft will significantly increase the contribution the aircraft can make to ATM.

Equipment ranging in capability from Area Nav (RNav) to Flight Management Systems is already in aircraft, being developed for delivery in the next generation of aircraft or being retro-fitted to existing aircraft. It is forecast that by 1990 70% of the aircraft in service will have the capability to achieve a high standard of navigation in areas where suitable ground aids are available, and of these 40% will also have the enhanced Flight Management System capability. These estimated percentages increase to 90% and 80% respectively by the year 2000.

The complementary improvements of ground aids must proceed in parallel with the development and implementation of airborne systems.

4 CONCLUSIONS

There is potential for fuel saving within the ATM system but that which may be achieved by improving the efficiency of future aircraft types has been estimated to be at least an order of magnitude greater. In addition airlines have scope to save fuel by increasing their own efficiency. However, the degree of improvement depends on the operating and maintenance techniques they have used previously.

The importance of creating an awareness of the need for fuel conservation, by education if necessary, and of minimising constraints must be appreciated. The main action, however, is the setting up of relevant Research and Development programmes and the subsequent implementation of worthwhile results of R and D. The UK has a Research and Development programme which already includes many items relevant to fuel conservation. In addition, studies are currently in hand on the feasibility of reducing vertical separation standards, on the possibility of more effective provision and use of meteorological data, and on the potential value of data-links between air and ground.

It is possible that some or all of these considerations will indicate the need for further R and D.

Finally, it is worth making the point that many of the above suggestions for saving fuel will themselves involve expenditure, either in the form of investment in capital equipment or caused by the adoption of more costly procedures. Ordinarily one would wish to see a financial benefit which exceeds the sums invested. However it is an interesting question, to which an answer is not attemped here, whether fuel is so precious a commodity that it is worthwhile incurring an actual increase in net expenditure in order to conserve it.

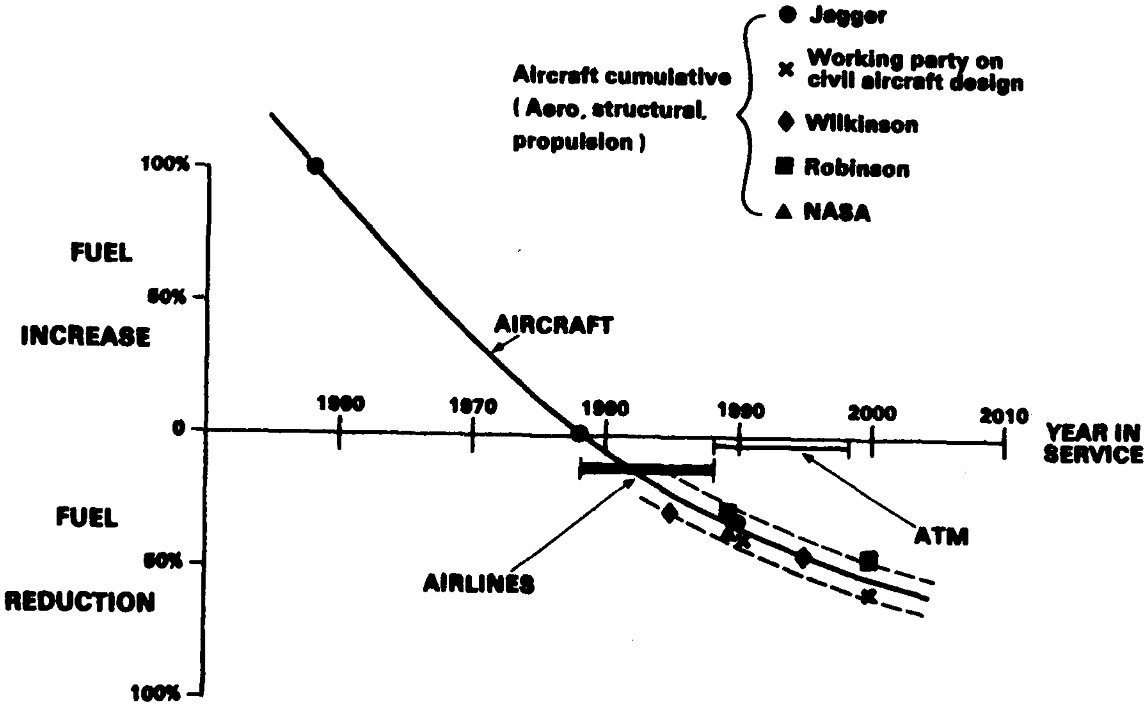

Fig. 1 Fuel savings – aircraft

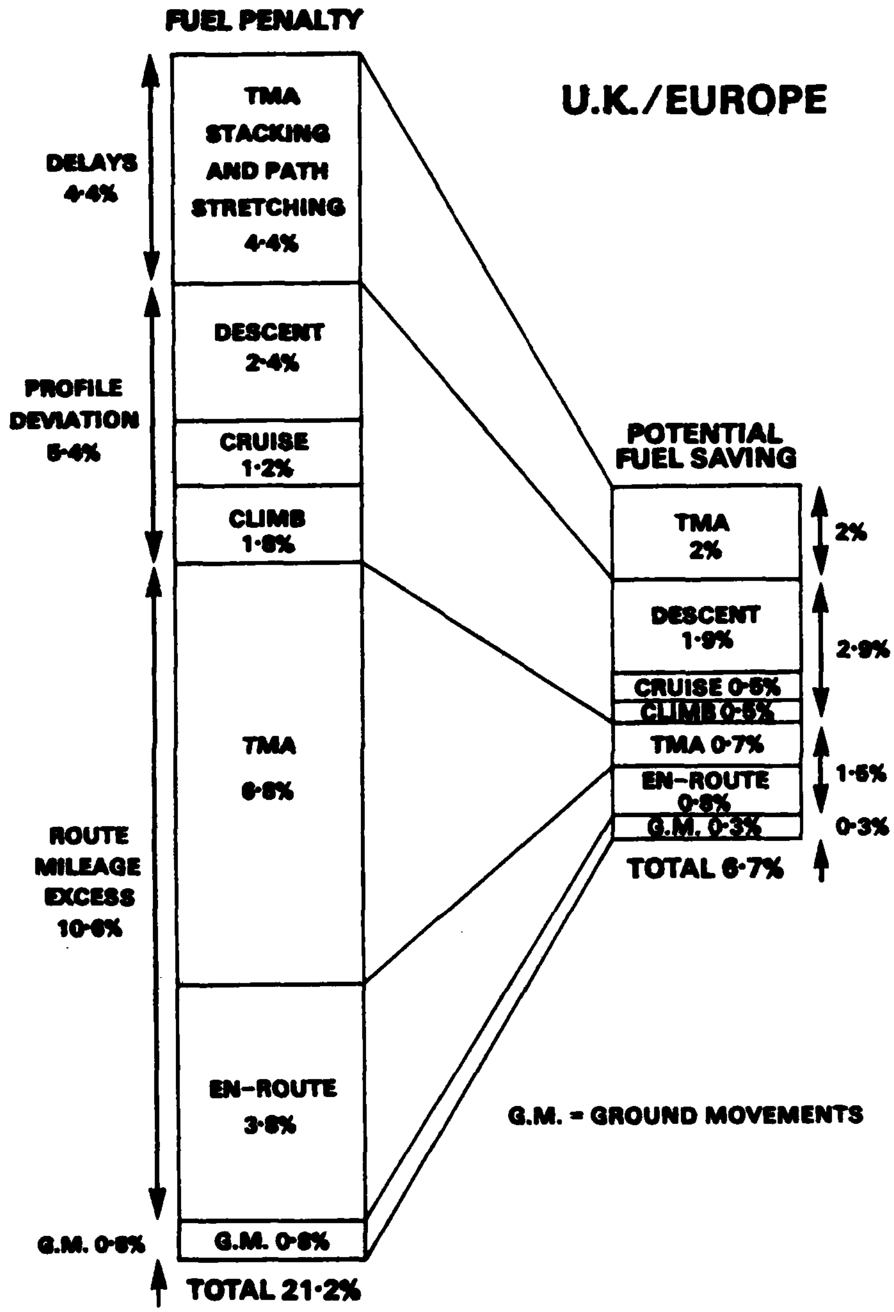
FUEL PENALTY
U.K./EUROPE
DELAYS 4·4%
TMA STACKING AND PATH STRETCHING 4·4%
PROFILE DEVIATION 5·4%
DESCENT 2·4%
CRUISE 1·2%
CLIMB 1·8%
ROUTE MILEAGE EXCESS 10·6%
TMA 6·8%
EN–ROUTE 3·8%
G.M. 0·8%
G.M. 0·8%
TOTAL 21·2%
POTENTIAL FUEL SAVING
TMA 2%
2%
DESCENT 1·9%
2·9%
CRUISE 0·5%
CLIMB 0·5%
TMA 0·7%
1·5%
EN–ROUTE 0·8%
G.M. 0·3%
0·3%
TOTAL 6·7%
G.M. = GROUND MOVEMENTS

Figure 2

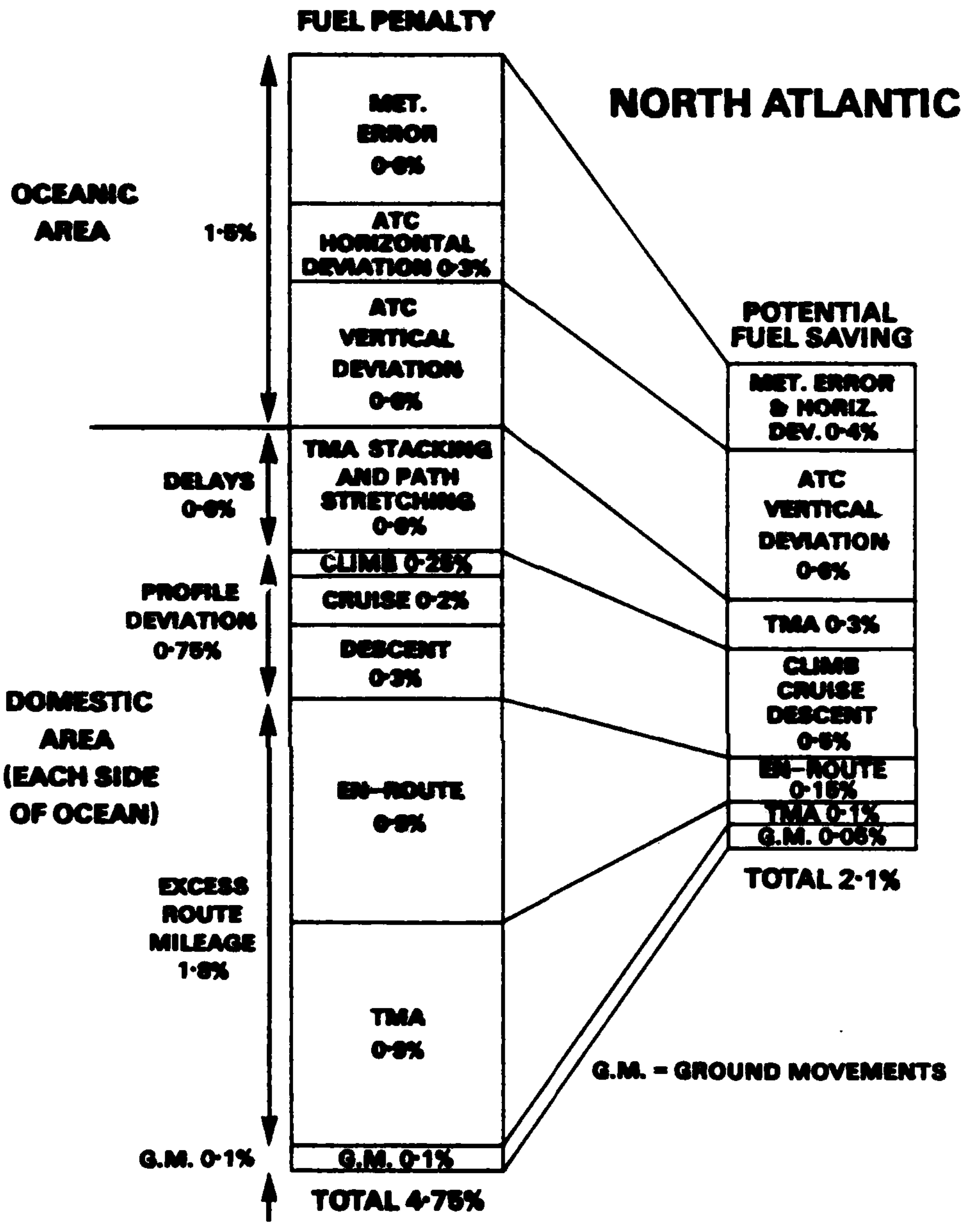
FUEL PENALTY
NORTH ATLANTIC
OCEANIC AREA
1·5%
MET. ERROR 0·6%
ATC HORIZONTAL DEVIATION 0·3%
ATC VERTICAL DEVIATION 0·6%
DELAYS 0·6%
TMA STACKING AND PATH STRETCHING 0·6%
PROFILE DEVIATION 0·75%
CLIMB 0·25%
CRUISE 0·2%
DESCENT 0·3%
DOMESTIC AREA (EACH SIDE OF OCEAN)
EXCESS ROUTE MILEAGE 1·8%
EN-ROUTE 0·9%
TMA 0·9%
G.M. 0·1%
G.M. 0·1%
TOTAL 4·75%
POTENTIAL FUEL SAVING
MET. ERROR & HORIZ. DEV. 0·4%
ATC VERTICAL DEVIATION 0·6%
TMA 0·3%
CLIMB CRUISE DESCENT 0·5%
EN-ROUTE 0·15%
TMA 0·1%
G.M. 0·05%
TOTAL 2·1%
G.M. = GROUND MOVEMENTS

Figure 3

Table 1

SUMMARY OF FUEL PENALTIES/SAVINGS FOR U.K./EUROPE & NORTH ATLANTIC OPERATIONS

REGION	% FUEL PER ANNUM		FUEL KILO-TONNES PER ANNUM		COST £M PER ANNUM AT CURRENT PRICES		
	FP	FS	FP	FS	FP	FS	UK SHARE
UK/EUROPE	21.2	6.7	635	200	140	43	9
NORTH ATLANTIC	4.7	2.1	505	225	110	49	14
WEIGHTED TOTAL	8.7	3.2	1140	425	250	92	23

FP = FUEL PENALTY

FS = FUEL SAVING

Data provided by CAA/DORA – July 1982

THE AIRLINE FACING THE PRESENT CRISIS

by

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INTRODUCTION

The impact of the drastic fuel price increase on airline operations is briefly discussed. Some measures that are being taken to contain the economic effect are reviewed. In particular ATC criteria and military constraints are highlighted, which are known to have a direct influence on fuel burn. This is illustrated with examples and furthermore a specific comment is made in relation to the Portuguese ATC environment.

DISCUSSION

Although speaking for airlines in general, some of the detailed data and examples are related to KLM that information was readily available. In any event that KLM information may be regarded generally representative for a typical airline.

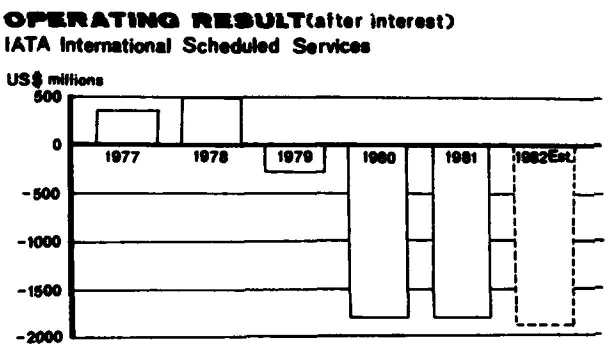


FIGURE 1

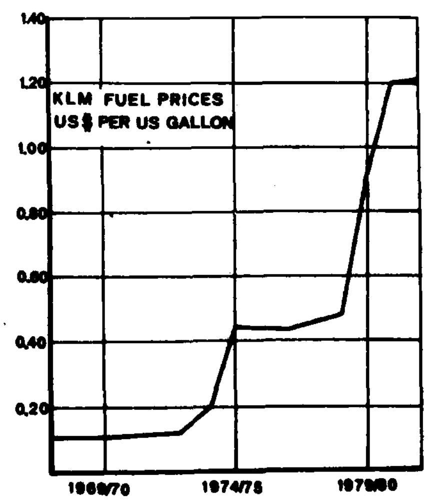


FIGURE 2

Figure 1 illustrates the alarming financial situation, where the airline industry is presently faced with. This can - obviously - not be fully attributed to the high kerosine prices (Fig. 2), but is largely due to the worldwide economic recession, in which the high oil prices are undoubtedly a factor.

INCREASE KLM FUEL COSTS AND USER CHARGES (DFL MILLIONS)	1972/73	1981/82
Operating Revenue	1279	3772
Fuel	132 (10.3 %)	1141 (30 %)
User Charges	91	243
Landing etc	82	154
En route	9	89

FIGURE 3

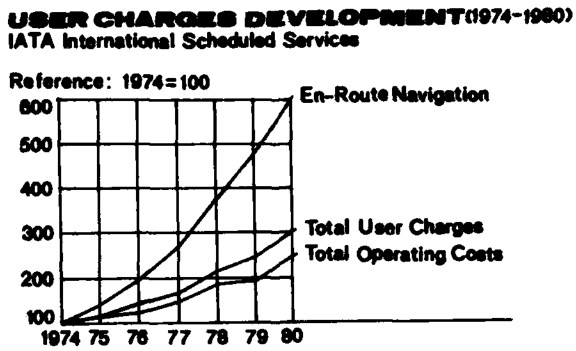


FIGURE 4

Figure 3 shows two main elements of KLM operating costs that have gone up rapidly since 1972, the year before the first oil crisis, viz. fuel and user charges. It appears that the KLM enroute charges have increased by a factor 10, whereas the number of miles flown has actually decreased by 7 %. This rapid increase of the enroute charges is also depicted in Fig. 4, which shows a 6 fold increase for IATA airlines over a period of 6 years. Further details as regards charges will not be discussed, except that it should be noted that airlines are more subjected to a multitude of charges for services and facilities and without always having the possibility to discuss the need for the facilities or the opportunity to negotiate the level of the charges.

Fuel consumption is set by a number of factors:

(1) A large and direct factor is - obviously - the planned airline operation. In the past fuel cost was relatively insignificant and operations were primarily determined by commercial considerations and other cost factors. This picture has changed completely now that fuel is a large variable cost element and - as a result - change of schedules and consolidation or cancellation of flights in case of low load factors is becoming common practice.

(2) Fuel efficiency of the fleet. Figure 5 shows that by replacing fuel inefficient aircraft by modern more efficient equipment, 44 % improvement in fuel efficiency has been achieved in the past decade by KLM. It is notable that notwithstanding a large increase in production the total fuel consumption has hardly increased. This trend will continue throughout the next decade with the implementation of modern aerodynamic developments: (supercritical wing, high aspect ratio, modest sweep back) and new technology engines. Boeing has estimated - for example - that such advances could make the 747 approx. 15 % more fuel efficient.

IMPROVEMENT FUEL EFFICIENCY OF KLM FLEET	1972/73	1981/82
Fuel used (liters, millions)	1315	1371
Available ton kilometers (millions)	2735	4111
Liters fuel used per available TKM	0.48	0.33

FIGURE 5

(3) In recent years airlines have paid much attention to improve the fuel efficiency of their current fleet and to adjust their operational practices. This includes better maintenance to reduce drag and improve engine efficiency. Also modifications are made to airframe and engines with the same objective. Some examples are given in Figures 6 and 7.
Although such activities are usually quite expensive, they can be cost-effective because of the high fuel price.

TYPICAL DRAG REDUCTION PROGRAMS

		Estimated fuelsaving
DC 9	Overall program for better trimming of seals and clearances	1 %
DC 10	Redesigned wing and tail fillets	1.5 %
747	Horizontal stabilizer leading-edge redesign	0.7 %
	Flap seal addition	0.1 %
	APU air scoop removal	0.12 %

FIGURE 6

TYPICAL ENGINE IMPROVEMENTS

		Estimated fuelsaving
747/P & W JT9	Fan case splitter removal	0.7 %
747/GE	CF6-5E to -50 E2 modification (includes new design fan blades)	1.5 %

FIGURE 7

(4) For proper understanding of the operational aspects, it should be realized that the fuel burn to fly a given aircraft from A to B is directly influenced by the following factors:

(a) Weight, which includes empty weight, equipment, crew, pantry, payload and fuel incl. fuel reserves. Airlines are paying these days a great deal of attention to aircraft and equipment weight saving and numerous changes for weight saving have been implemented in the past years.
As an example, KLM recently replaced the seatbelts on all its aircraft with belts with light-weight buckles. The costs were recovered in 1.3 years.
Fuel reserve is a significant factor, especially on long distance flights: for each 1000 kg fuel carried unnecessarily on a AMS-JFK flight approx. 300 kg is burnt. Operation with tight reserves requires accurate planning and execution of the flight and full understanding and cooperation from the part of ATC controllers.

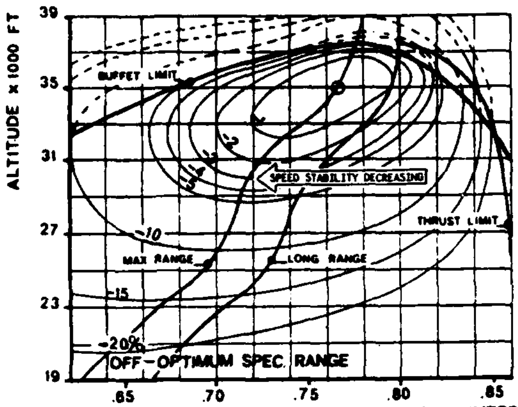
(b) Airdistance flown has obviously a direct impact on fuel burnt. Aircraft have - in principle - and especially those equipped with modern navigation systems, the capability to fly direct from A to B. Unfortunately, this cannot be realized in day to day operation because of military constraints and since the route structure and ATS procedures have evolved without sufficient attention to airline costs. These constraints are particularly restrictive in Europe with a great number of states, each having the prerogative to make its own decisions. It is true that ATC does not always have adequate tools to enable them to ensure standard separation on more direct routes or for ad hoc direct clearances but this applies only to some parts of Europe.

A recent Eurocontrol study on city pair distances in 11 European States has revealed an average of approx. 7 % extra miles flown when compared with the great circle distance between defined exit and entry points for those cities. A similar exercise in the USA revealed 3 % exceedance.
Holding also adds to airdistance and is - as such - a most inefficient way to operate an aircraft. Although holding or path stretching can never be avoided completely, recent US and Eurocontrol studies indicate the feasibility to reduce this inefficiency to a large extent.
In addition to the published route, there may be possibilities to fly more direct tracks where traffic conditions permit. Such clearances are common practice in the USA and are occasionally issued in Europe.

In Europe there is certainly potential for more wide spread use of ad hoc direct clearances and this subject will be actively pursued (by IATA) in the Committee for European Airspace Coordination (CEAC).

(c) Finally speed and altitude at which an aircraft is cruising do have a large effect on the fuel burn per mile. This is illustrated in a somewhat complicated graph (Fig. 8) which shows that at each weight there is one unique fuel optimum speed and altitude. The optimum altitude increases at a rate of 800 - 1000 ft per hour as the fuel is burnt off and the aircraft weight decreases accordingly. Small speed and altitude deviations from optimum have a relatively minor effect but Fig. 8 shows that the penalties increase rapidly as the deviations increase and that there are some other considerations and constraints which may affect optimum operation.

Furthermore several other flight operational factors affecting the fuel consumption have been optimized in recent years, such as takeoff, descent and landing procedures and lately performance computers and flight management systems are installed in aircraft to assist the pilot to operate in a more optimal way.



EFFECT OF ALTITUDE AND MACH ON SPEC. RANGE

FIGURE 8

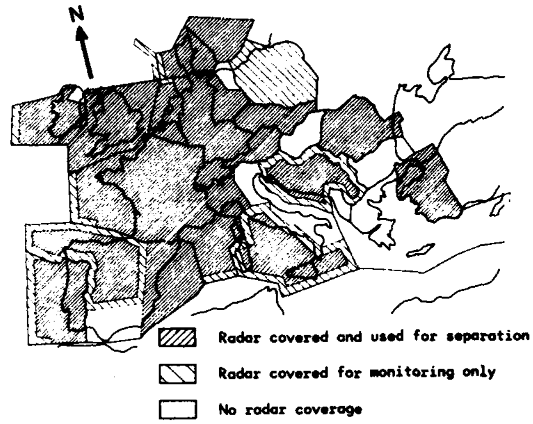


FIGURE 9

The following comments relate to civil ATS aspects in Europe:

- It is well-known that for efficient ATC full radar coverage is an indispensible element. Fig. 9, presenting information supplied to ICAO by States in 1981, shows that this is not realised in certain parts of Europe. Lack of the availability of radar, or lack of exploitation of existing radar leads to delays and to assignment of undesirable (non-optimum) flight levels and routings.

- The typical ATS structure in Europe requires full attention to ATS automation and - in particular - to better coordination/communication between adjacent ATS units.

- Noise sensitive areas and associated departure and arrival routings cause significant additional costs to airlines. In view of energy conservation and the introduction of "low noise" aircraft, reconsideration of noise constraints at certain locations would seem desirable.

Because, this audience is NATO related, citing of examples of fuel penalties caused by military restrictions is appropriate.

- The reservation of airspace during weekdays or permanently for military purposes. While it is appreciated that efforts have been made to permit civil aircraft to cross reserved airspace, it is felt that much more could be done when there is no military necessity to use them. However, good military/civil coordination is essential; the unit which controls the military area should take the initiative, and inform the civil ATS authorities of the temporary opening of the area, so that it can be utilized for ad-hoc direct clearances. When the temporary opening of the restricted area is known well in advance the ATS Reporting Offices could be advised, in order to give the operators the opportunity to plan the flight accordingly, which means less fuel to carry. Fig. 10 shows a typical direct "weekend" route and it would appear that this same route - with some goodwill - could be made available in weekdays during certain periods of the day.

- It is felt that there is a case for a joint civil/military review of restricted airspace: restricted areas and the associated airway structures have been in existance for many years and a restatement of civil and military needs and preferences could well lead to solutions beneficial to both parties. This does not necessarily mean less restricted airspace.

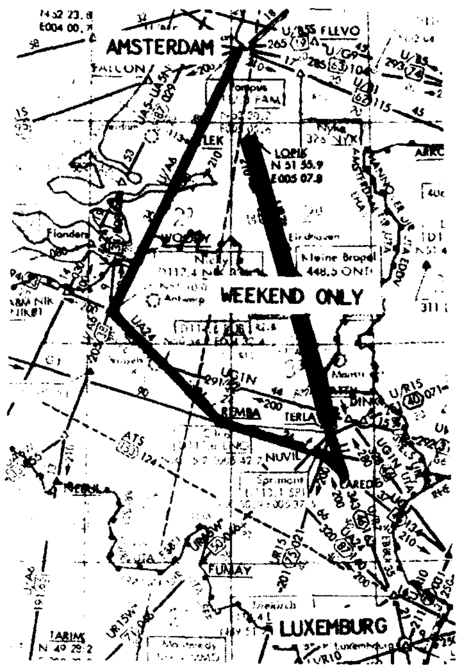


FIGURE 10

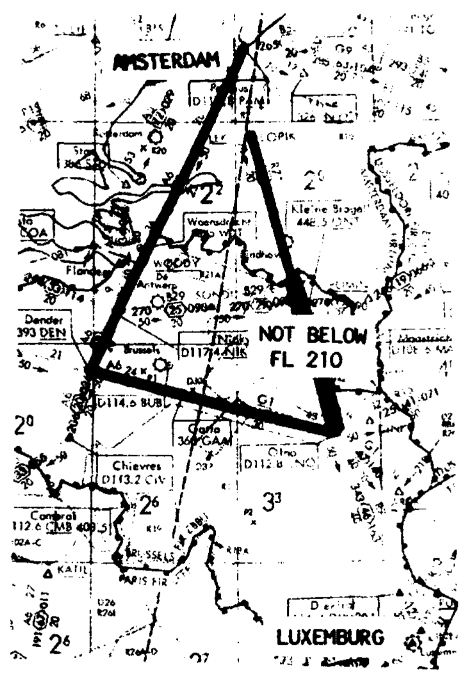


FIGURE 11

- In certain cases reservation of airspace applies to particular flight levels. This could probably also be done in a less restrictive way by opening blocked flight levels during periods of time that there is no real military need. Blocking of low levels may require rerouting as shown in Fig. 11 and induce significant additional route distance whereas blocking of high levels may also cause greatly increased fuel burn as explained in Fig. 8.
Figures 12 and 13 show typical situations of this nature in Germany and Spain.

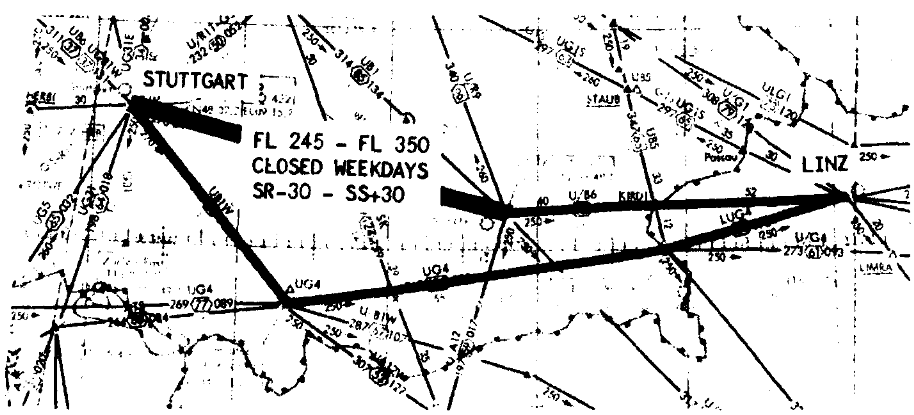


FIGURE 12

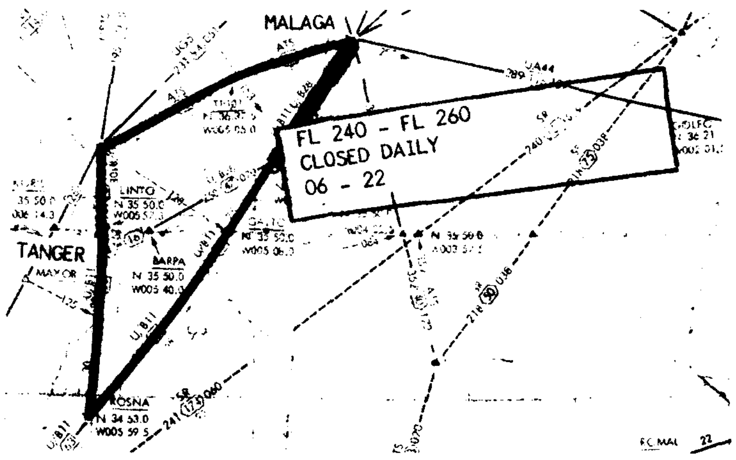


FIGURE 13

- The use of AWACS is in the Middle East restrictive for civil traffic, as the operation is blocking a number of flight levels on very busy trunk-routes. Airlines are concerned about the forthcoming AWACS introduction in Europe. However, with very efficient civil/military coordination, the use of AWACS can be made as little restrictive as any other aircraft crossing the airways.

- Large scale military exercises. These exercises should in principle be held outside the areas where major trunk-routes run. Furthermore, with good civil/military coordination, complete blocking of airspace can be avoided. Airlines have - for instance - suffered significant penalties during the US Navy exercises in the South China Sea and in the Caribbean. I must add that our experience in this respect in Western Europe is in general satisfactory.

The following could contribute to save costs:

- Thanks to the navigation accuracy the buffer-areas for many modern aircraft with the advanced navigation systems could be reduced. This could mean mileage saving as well as ATC capacity enlargement. This development - obviously - requires further study.

- Until full civil radar coverage is achieved, the use of selected military radar data in the civil ATS units would provide a better picture of the traffic situation and therefore give clearances which are more optimal for many flights.

- Setting up of a coordination unit when several units of different Military Forces are using the same restricted area. Such a unit must then coordinate with the civil ATS unit about temporary use of airspace.

One final remark related to the Portuguese ATS situation. Many long distance flights from Europe to South America and the Caribbean cross Portuguese airspace. Although modern flightplanning computers have the capability - when loaded with the appropriate weather data - to work out the optimum/minimum fuel routing on a flight to flight basis, only a number of fixed routings is permitted to be flown on certain hours of the day. (see Fig. 14). It is submitted that significant fuel savings are feasible by operating optimum routes and this applies in particular to these long distance flights. The present situation may be attributed largely to inadequate equipment to cope with the traffic demand in the New York Oceanic Control Area.

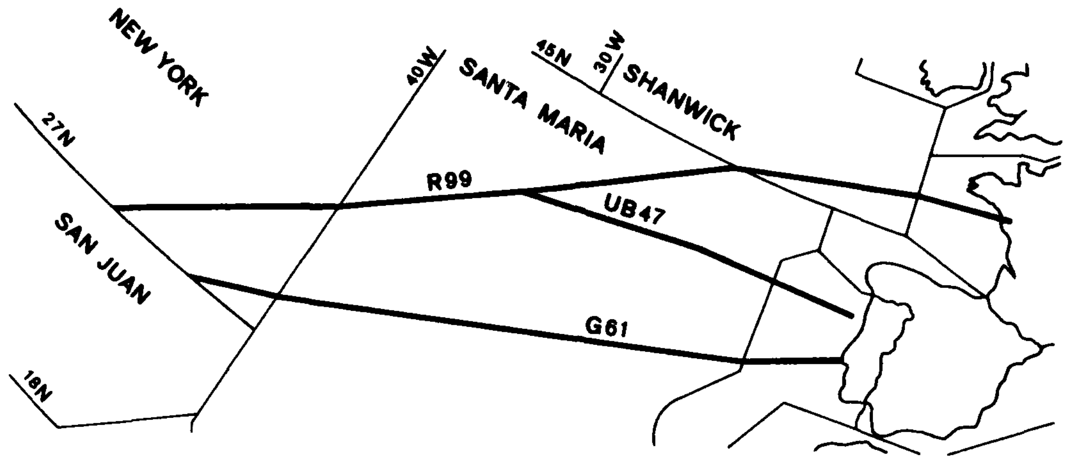


FIGURE 14

CONCLUDING REMARKS

In this presentation the grave overall financial situation of the airlines has been highlighted as well as cost elements that have increased very rapidly in the last decade, such as fuel and route charges. Several of the airline activities to reduce fuel consumption have been discussed in some detail and special attention is drawn to operational constraints causing fuel penalties that are outside the area where airlines have direct control, viz. ATC and military constraints.

Although it is fully understood how the present constraints have evolved in the course of the years, it is emphasized that for successful fuel saving it is of utmost importance that all potential ways and means to save fuel are exploited to their fullest extent. Hence, the airline's humble request to ATC and to military authorities is to sit together to review existing constraints and aim at solutions which could - at the end - well prove beneficial to all concerned.

LES BESOINS MILITAIRES

par

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En raison de la nature des contraintes qui frappent l'usager militaire, mérite d'être posée la question de savoir dans quelle mesure le contrôle du trafic peut contribuer à résoudre les problèmes actuels qui débordent largement la question des prix des carburants.

Au cours de la première partie de l'exposé, une esquisse du cheminement aboutissant à l'approbation du budget de la Défense dans les pays membres de l'Alliance Atlantique illustre combien il est difficile dans les démocraties occidentales, d'obtenir en cette période de crise, les crédits nécessaires à l'exécution des programmes de défense collective élaborés par l'OTAN en consultation avec les pays membres de l'Alliance et approuvés par les autorités gouvernementales.

La seconde partie évoque les résultats concrets obtenus ces dernières années grâce à la coordination entre les partenaires civils et militaires responsables de la gestion de l'espace et laisse entrevoir des modes d'actions susceptibles de contribuer à une forme d'économie des précieux carburants. Ces gains paraissent dérisoires lorsque se pose dans toute son acuité la question des moyens nécessaires pour la réalisation d'une politique délibérément consentie.

Je souhaiterais préciser, en commençant cet exposé, que je prends la parole non pas en qualité de représentant d'un QG interallié mais en raison de l'expérience acquise en matière de contrôle du trafic aérien.

Lorsque j'ai été approché pour couvrir le point de l'ordre du jour relatif aux besoins de l'usager militaire face aux contraintes économiques, j'ai hésité un instant avant d'accepter cette invitation. Pourquoi? Tout simplement parce que les contraintes économiques auxquelles l'usager militaire est appelé à faire face aujourd'hui sont d'ordre multiple : d'abord l'augmentation des prix des carburants, ensuite les fluctuations des cours des monnaies nationales, enfin la récession économique et l'incidence de cette dernière sur le budget de la défense et la réalisation des programmes de défense. Il me paraissait dès lors évident que la contribution que pouvait apporter le contrôle du trafic aérien à la solution des problèmes actuels de l'usager militaire ne pouvait être que marginale.

Mon exposé comprend deux parties. Au cours de la première, je me propose d'illustrer combien il est difficile dans les démocraties occidentales, d'obtenir en cette période de crise, les moyens financiers nécessaires pour remplir les missions de défense.
Au cours de la seconde, je me propose de souligner comment le contrôle du trafic aérien peut contribuer à rentabiliser au mieux la partie du budget réservée aux prestations de vol.

L'établissement du budget national est une prérogative gouvernementale qui doit en principe, rencontrer entre autres choses, les obligations résultant d'accords internationaux. Il s'agit, et c'est important de le souligner, d'un exercice annuel. Le budget de la défense, l'une des facettes de ce budget national, est soumis à ces règles fondamentales et tient compte des obligations résultant du Traité de l'Atlantique Nord.

Dans les démocraties occidentales, le budget de la défense reste malgré tout, l'un des budgets les plus élevés. Il est certainement l'un des plus contestés. En vue de son approbation, nombre de justifications détaillées doivent être présentées si bien que celui qui dispose du temps nécessaire peut en retirer une foule de renseignements significatifs au sujet de l'aptitude au combat de nos forces armées.

Je ne puis m'empêcher de souligner le paradoxe qui existe entre, d'une part, les infimes précautions qui sont prises pour dénier à un ennemi potentiel toute possibilité de se procurer des renseignements relatifs à nos armements, nos stocks de guerre, nos effectifs et d'autre part, la facilité d'accès pour un chacun à la multitude de détails précis fidèlement consignés dans les documents parlementaires concernant le budget de la défense.

Trois phases président à l'établissement de ce dernier :
- La préparation du projet de budget par les chefs d'état-major responsables de la mise en condition de leur force ;
- L'acceptation du projet de budget par le ministre de la défense ;
- L'approbation du projet de budget par le gouvernement.

La préparation du budget est une opération difficile parce qu'elle doit être entreprise à un moment où les instructions relatives à la présentation du projet de budget ne sont pas encore disponibles. La préparation du budget est également une opération complexe nécessitant une parfaite coordination au niveau de la gestion des différentes forces. Les éléments majeurs sont puisés dans les plans de défense collective préparés par les organes militaires internationaux et approuvés par les autorités gouvernementales des pays membres de l'alliance. Le principe qui prévaut à l'établissement de ces plans OTAN est que la défense doit s'établir sur une base économique et sociale solide et qu'il ne faut demander à aucun état de supporter des charges de défense qui dépasseraient ses possibilités.

La procédure des examens des plans de défense OTAN comporte les stades suivants :

1. - L'établissement des hypothèses générales sur lesquelles seront fondées ces examens. Ces hypothèses sont formulées chaque année par l'OTAN sur base d'une évaluation des risques de guerre d'une part et d'autre part sur la situation économique et politique des pays membres de l'Alliance.
2. - La soumission aux gouvernements des pays membres d'un questionnaire détaillé portant sur leurs programmes militaires, leurs budgets, leurs plans de production et leur situation économique générale.
3. - La communication par les commandements suprêmes de directives relatives à l'amélioration des forces existantes et les recommandations du comité militaire après évaluation de ces directives militaires.
4. - L'analyse des réponses nationales afin d'établir une comparaison entre les besoins de l'OTAN et les programmes nationaux de défense et de souligner les problèmes importants qui se posent à chaque pays.
5. - La formulation de recommandations par les autorités militaires de l'OTAN et le Secrétariat international sur les ajustements indispensables pour aménager les plans nationaux en fonction de l'analyse qui vient d'être évoquée et pour tendre vers une répartition équitable du fardeau économique et financier de la défense collective.
6. - La discussion multilatérale de l'effort de défense dechaque pays en vue d'obtenir un accord d'ensemble répondant aux objectifs de l'alliance et aux possibilités de chacun des pays membres.
7. - La communication aux gouvernements du rapport fixant les objectifs de forces pour chaque pays et énonçant les problèmes essentiels qui se posent à l'alliance pour les cinq années à venir.
8. - La discussion et l'approbation au niveau du conseil de l'Atlantique Nord réuni en session ministérielle de ce plan quinquennal, les pays ne prenant toutefois un engagement ferme que pour la première année d'application.

Dans le cadre pluriannuel de ce plan quinquennal, les chefs d'Etat-Major peuvent élaborer leurs programmes annuels de mise en condition de leur force. Ces programmes sont établis pour atteindre les objectifs globaux fixés par le ministre de la défense en fonction des missions et des moyens financiers et humains prévisibles pour remplir ces missions. Schématiquement ces programmes peuvent être subdivisés en dépenses ordinaires et en programmes d'équipement et d'infrastructure s'échelonnant sur une période de cinq ans et parfois davantage. C'est à ce moment qu'apparaissent les premières difficultés du fait que, traduits en chiffres, programmes et prévisions se soldent par une estimation globale considérée comme trop élevée. C'est aussi à ce moment que commence un premier travail de recherche d'économie. Trois formules sont traditionnellement appliquées séparement ou conjointement :

- La suppression de crédits pour des programmes dont la réalisation est postposée.
- La compression de certains crédits après un calcul "au plus juste" des besoins.
- L'étalement des crédits pour des programmes à réaliser au cours de périodes plus longues qu'initialement planifiées.

Au terme de cet exercice, des estimations des coûts de réalisation des programmes sont présentées au Ministre de la Défense. De deux choses l'une : ou ces estimations sont acceptées et à ce stade, l'affaire est entendue ou ces estimations sont rejetées parce que considérées une nouvelle fois comme trop élevées à la lumière de la situation politique, économique et sociale du moment. Et de nouvelles économies doivent alors être recherchées! En fin de compte, on arrive quand même à des estimations acceptables. La partie n'est pas gagnée pour autant! A ce moment en effet, sont déposés les projets de budget pour tous les départements et ce serait miracle, en cette période difficile, que l'enveloppe escomptée pour l'année budgétaire en préparation ne soit pas crevée. A ce stade, il n'est pas exclu qu'un nouvel effort d'économie soit exigé de la part du département de la défense. Ainsi, après un long et pénible cheminement le budget de la défense sera finalement approuvé. Cela n'implique pas pour autant que l'exécution de ce budget va se dérouler sans anicroche. Que du contraire, au cours de cette phase vont se faire jour des problèmes pratiques que je vais tenter de synthétiser.

Une partie du budget approuvé va servir à financer l'achat d'équipements neufs faisant l'objet d'un contrat qui prévoit entre autre dans quelle monnaie les factures doivent être acquittées. Un quelconque écart dans les taux de change entre la monnaie nationale et la monnaie convenue pour le paiement pose des problèmes évidents qui n'enlèvent rien aux obligations contractuelles. En termes clairs, il faudra, dans le cadre du

budget approuvé, trouver les ressources supplémentaires pour faire face à ces obligations. Cela ne pourra être réalisé qu'au détriment d'autres articles du budget en sachant fort bien que certains d'entre eux comme par exemple les dépenses relatives au personnel sont incompressibles. Il tombe sous le sens qu'en cette époque où la majorité des pays membres de l'alliance ont des programmes majeurs en cours, les problèmes financiers à résoudre sont nombreux.

Arrêtons-nous un instant à l'article du budget relatif aux carburants avion. Pour l'année budgétaire en cours, le chef d'Etat-Major a établi le plan de vol pour sa force en tenant compte des directives du SHAPE en la matière. Ce plan de vol peut être converti en litres de carburants. Hélas, ce ne sont pas ces volumes de carburants qui sont approuvés ; c'est l'estimation de leurs coûts. Comme la tendance actuelle n'est pas à la baisse dans le secteur pétrolier, il est probable qu'avec les crédits approuvés moins de carburant pourra être acheté. Comme par ailleurs d'autres articles du budget ont déjà dû être rabotés, il en résulte que le plan de vol risque d'être compromis. Il va de soi que tout sera mis en oeuvre pour éviter semblable issue mais la menace est réelle.

Ce sont ces réalités qui me faisaient dire en début d'exposé que je craignais que, dans les circonstances présentes, le contrôle du trafic aérien ne pouvait apporter qu'une contribution marginale à la solution des problèmes avec lesquels l'usager militaire se débat pour l'instant.

Dans ce qui précède, je n'ai pas voulu décrire la procédure d'établissement propre à un pays en particulier. J'ai essayé de dégager les lignes directrices communes à l'ensemble des pays membres de l'alliance. Je crois que les contraintes et les difficultés soulignées sont d'un autre ordre que celles que sont appelées à affronter aujourd'hui et l'aviation générale et l'aviation de transport public. Pour l'aviation civile qui reste une entreprise commerciale, la règle d'or de l'offre et de la demande reste d'application si bien que l'augmentation des coûts d'exploitation des entreprises peut, à tout le moins en partie, être répercutée sur le client. Je veux bien concéder que cet argument n'est pas tout à fait de mise pour les compagnies nationales de transport qui, pour des raisons de prestige, voient leur liberté d'action sérieusement limitée. En contre-partie toutefois, je sais, nous savons tous, qu'en cas de passif en fin d'année, ces dernières sont assistées par des crédits spéciaux alloués par leur gouvernement.

Voyons à présent comment les services de contrôle du trafic peuvent contribuer à rentabiliser au mieux la partie du budget consacrée à l'acquisition des indispensables carburants.

Imaginons une base aérienne implantée d'une manière telle que toutes les activités requises pour l'entraînement et le maintien en condition opérationnelle des équipages puissent être exécutées sans aucune forme de restriction. Par activités requises, j'entends la conversion sur un nouvel avion de combat, l'entraînement au vol à basse altitude, l'entraînement au tir air-sol, l'entraînement au tir air-air. Il n'est pas déraisonnable de présenter un éventail aussi large pour les besoins d'entraînement du fait que le principe est acquis à présent qu'un même pilote peut être appelé en fonction des besoins, à exécuter soit des missions de défense aérienne, soit des missions de chasseur-bombardier. Il est évident que dans cette hypothèse toute académique où sont écartés d'emblée tous les problèmes d'espaces associés aux activités d'entraînement évoquées les services de contrôle du trafic auront un rôle limité à garantir la sécurité aérienne durant les phases de décollage et d'atterrissage et à assurer la coordination des activités générées à partir de cette base. Leur rôle est primordial mais un minimum de temps, en d'autres mots un minimum de carburant y est consacré.

De par le monde, ces conditions d'opération idéales sont rarement rencontrées. Elles ne le sont certainement jamais dans la région Centre Europe où de multiples contraintes résultent d'une part de l'obligation de coordonner l'emploi de l'espace aérien avec d'autres usagers, d'autre part du degré d'occupation du sol par d'autres activités humaines. Il n'empêche que, ne fût-ce que pour des raisons de sécurité aérienne, la majorité des activités aériennes militaires est organisée dans des espaces qui ne sont pas assujettis à des règles strictes de contrôle du trafic aérien. Dans la région Centre Europe, en raison des densités de trafic enregistrées, des espaces de ce type sont plus que jamais nécessaires. Leur création et partant les activités militaires qui y sont associées ne sont rendues possibles que grâce à une coordination souvent difficile, toujours indispensable en temps de paix , entre partenaires civils et militaires responsables de la gestion de l'espace.

Il existe par ailleurs un certain nombre d'activités militaires, telles les missions de transport et les vols de transit, qui bénéficient des services de contrôle et d'information en vol tels que définis par l'Organisation de l'Aviation Civile Internationale(OACI). Pour leur bon déroulement, ces vols nécessitent eux aussi, une forme de coordination entre partenaires civils et militaires.

Ainsi donc, l'expérience prouve que cette coordination civile-militaire revêt à la fois un caractère théorique et un caractère pratique.

Il y a bien longtemps déjà que s'est amorcé ce processus de coordination. Il s'est manifesté pour la première fois lors de la création et de la mise en place du réseau des voies aériennes. A cette époque, au début des années '50, les forces aériennes s'orientaient déjà vers la mise en oeuvre d'avions à réaction, dont les altitudes de rendement optimum s'étendaient entre 25.000Ft et la tropopause. L'aviation commerciale exploitait des appareils dits "conventionnels" dont le plafond opérationnel ne dépassait pas les

20.000Ft. Cet état de fait avait une conséquence heureuse ; il conduisait "de facto" à la ségrégation des circulations civiles et militaires et laissait intacte la liberté d'action souhaitée par les forces aériennes à haute comme à basse altitude.

Au cours des années '50, l'aviation civile aligne un nombre sans cesse croissant de turbo-propulseurs dont le plafond opérationnel gravite autour de 25.000Ft. L'aviation générale prend naissance mais ses ambitions sont encore fort limitées. Sur le plan de la structure de l'espace, la coordination civile-militaire intervient pour la création des UTAs et les adaptations nécessaires aux espaces de procédures de décollage et d'atterrissage. L'extension verticale du volume exploité par l'aviation civile ne porte guère atteinte à la liberté d'action de l'aviation militaire qui voit son plafond opérationnel s'élever largement au-dessus de la tropopause.

De la fin des années '50 à nos jours, l'aviation connait un essor sans précédent.

Du côté militaire, les moyens aériens deviennent encore plus performants, mais cette période se caractérise surtout par le fait que l'hélicoptère a conquis sa place comme outil de combat.

L'aviation générale connait un développement prodigieux et l'éventail de ses activités la fait oeuvrer à tous les niveaux de l'espace aérien.

L'aviation commerciale passe à une mise en oeuvre généralisée de l'avion à réaction. Des performances accrues en matière de vitesse et plafond opérationnel entraînent comme conséquence une intense circulation d'appareils civils dans la tranche d'altitude utilisée jusqu'alors par l'aviation militaire. Sur le plan de la structure de l'espace, elles rendent nécessaires l'établissement du réseau des routes prédéterminées encore en usage aujourd'hui.

La conséquence de ce développement parallèle des aviations civiles et militaires est une utilisation de l'espace qui rend impossible à priori toute ségrégation des trafics. Comment dans ces conditions, garantir la sécurité aérienne de l'ensemble des usagers de l'espace ? Comment par ailleurs garantir la liberté d'action pour les forces aériennes.?

Ces questions étaient d"importance". La coordination entre responsables de la gestion de l'espace aboutit au principe suivant lequel le contrôle civil conduit le long des routes prédéterminées la circulation aérienne générale qui évolue selon les règles de l'OACI tandis que le contrôle militaire traite la circulation opérationnelle de manière à éviter cette circulation aérienne générale en toute circonstance. Ce principe entraîne pour les organismes de contrôle civils l'obligation de transmettre les informations nécessaires aux unités de contrôle militaires concernées. Il en résulte, pour les partenaires civils et militaires, l'obligation de disposer de moyens d'acquisition, de traitement, d'affichage et de transmission des informations dont les exigences de fiabilité et de rapidité ne peuvent être satisfaites que grâce aux techniques les plus élaborées. Le but était en fait de doter les contrôleurs civils et militaires de la même image aérienne afin de permettre lorsque nécessaire, une coordination de contrôleur à contrôleur.

Ainsi, sous la pression de l'évolution technologique des matériels aéronautiques, les responsables civils et militaires ont consenti aux investissements nécessaires à la mise en place des moyens répondant au souci commun de sécurité aérienne et sauvegardant l'indispensable liberté d'action pour la circulation opérationnelle militaire.

Aujourd'hui que les densités de trafic observées sont en diminution, l'usager militaire pour qui la mission n'a pas changé, espère que l'outil de contrôle mis en place va lui permettre de tirer le meilleur parti du carburant dont il dispose.

Je suis pour ma part convaincu que, là encore, une coordination civile-militaire bien pensée, bien organisée peut contribuer à sauver de coûteuses minutes de vol.

Au décollage par exemple, les avions de la nouvelle génération sont à ce point performants que le plafond opérationnel peut être atteint dans les limites de la zone de contrôle de l'aérodrome de départ. Dans le cas où voies aériennes et routes prédéterminées surplombent la base de départ, une coordination appropriée entre les services de contrôle civils et militaires concernés devrait permettre le décollage et la montée en postcombustion au travers de ces structures civiles dans les meilleurs conditions de sécurité.
De la sorte, pourrait être épargné le temps nécessaire, le carburant nécessaire pour gagner en vol horizontal à vitesse réduite le point de départ pour la montée opérationnelle. Le gain ainsi réalisé n'est pas tellement important mais accumulé pour chaque mission, il devient significatif.

Au retour de mission, des économies peuvent également être escomptées. La précision des instruments de navigation de bord et la qualité de l'outil de contrôle permettent d'exploiter au mieux les caractéristiques de vol des avions de combat au cours des procédures de percée et d'atterrissage. Une parfaite coordination entre tous les services de contrôle concernés qui disposent de la même image aérienne devrait permettre d'éviter toute manoeuvre inutile. Il est opportun de rappeler dans ce contexte que les quatre minutes nécessaires pour effectuer un virage de procédure de 360° représente 5% de l'endurance d'un intercepteur de la dernière génération.

La phase "en route" de certains vols militaires mérite également quelque attention. Nombre d'activités s'amorcent par une phase de mise en place des moyens. Je pense à certains exercices interalliés, aux entraînements au tir, aux échanges d'escadrilles.Cette mise en

place nécessite ce que j'appellerais des vols de transit qui, comme des avions de transport, empruntent sur une partie de leur trajet le réseau des routes aériennes contrôlées par les services civils. Au cours de ces vols qui en fait n'apportent rien à l'entraînement opérationnel des équipages, la meilleure coordination civile-militaire peut contribuer à des économies en allouant pour ces missions les niveaux de vol les mieux appropriés et en évitant surtout des procédures d'attente lors des transferts de contrôle. Ces actions vous pouvez m'en croire seraient rentables'.

A présent que toute une série d'activités civiles ou militaires sont organisées dans des espaces dont la réservation temporaire est annoncée par NOTAM, il n'est pas inutile d'insister sur la nécessité de signaler aux services de contrôle responsables l'instant où cette réservation n'a plus de raison d'être. Cette action relève du bon sens. Et pourtant que de fois observe-t-on des trajectoires évitant des zones réservées devenues inutiles. Une attitude moins négligente profiterait aux autres usagers.

Voilà quelques modes d'action qui selon mon expérience, peuvent contribuer à des économies de carburant. Ils sont efficaces mais il faut se garder d'en amplifier les résultats.

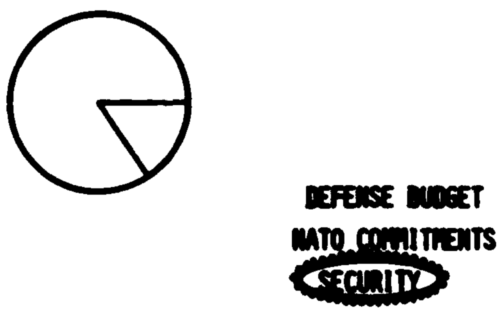
En raison de la situation inextricable que l'usager militaire vit aujourd'hui, ils peuvent contribuer à ce qui est vital : permettre aux forces aériennes de maintenir la condition opérationnelle pour remplir la mission en espérant que demain les gouvernements soient dans la possibilité d'allouer les moyens appropriés à la politique de défense collective établie de concert et approuvée de commun accord.

1. STEPS FOR THE ESTABLISHMENT AND APPROVAL OF THE DEFENSE BUDGET - REDUCTIONS AND CUTS

2. ATC'S CONTRIBUTION TO THE OPTIMIZATION OF THE BUDGETARY ALLOCATION TO FLYING HOURS

NATIONAL BUDGET

- GOVERNMENT'S PREROGATIVE
- ANNUAL EXERCISE



NATO PLANS APPROVED BY GOVERNMENT

BUDGET PREPARED BY COS

? REDUCTIONS ?

- ACCEPTED BY MINISTRY OF DEFENSE

? CUTS ?

- APPROVED BY GOVERNMENT

EXECUTION

- EXCHANGE RATE
- CONTRACTUAL COMMITMENTS

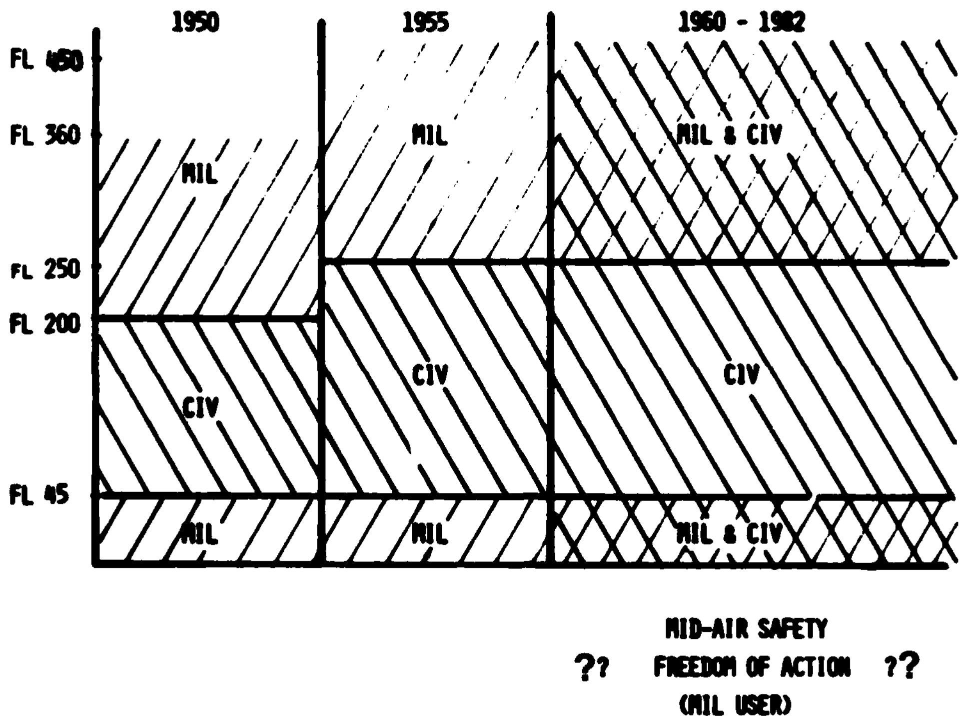
IDEAL BASE: ALL TRAINING FACILITIES
WITHOUT ANY FORM OF RESTRICTION

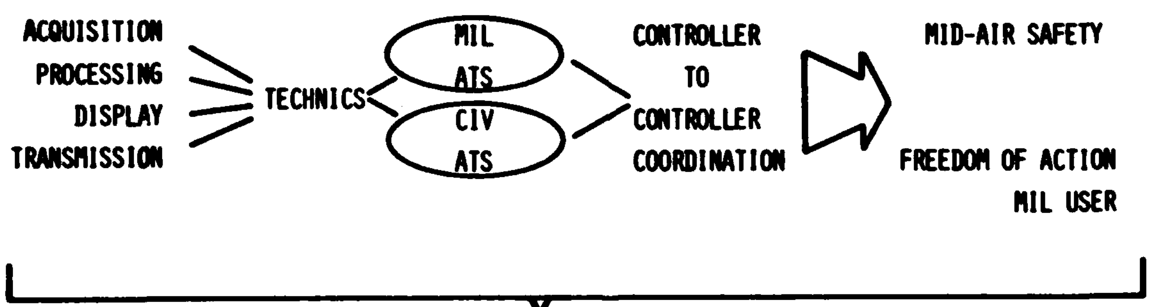
ATS ROLE IS VITAL BUT MINIMUM TIME = MINIMUM FUEL

??? C E N T R A L R E G I O N ???

TEMPORARY RESERVED AREAS

CIVIL-MILITARY COORDINATION





- F U E L C O N S E R V A T I O N -

- TAKE OFF & CLIMB
- DESCENT & LANDING
- EN ROUTE PHASE
- TEMPORARY RESERVED AREAS

AIR TRAFFIC SERVICES IN PORTUGAL

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SUMMARY

This paper presents the Portuguese area of responsability for the provision of Air Traffic Services; the organization of services and authorities are described. An overview is given of development projects, for the Lisboa and Santa Maria FIR's, their objectives, basic concepts,and implementation dates.

1. AREAS OF RESPONSABILITY

The Portuguese area of responsability for the provision of Air Traffic Services is, in extension, the largest of any Western-European Country; in east-western direction, it goes from the Spanish border to 40º West, extending from 45º North to 17º North in its southernmost point.

To give an impression of this airspace dimensions, it is equivalent to the area between Lisboa and Viena in one direction, and between Casablanca and Stocholm, in the other (traffic densities beeing not comparable, of course). The areas of portuguese responsability are shown of fig. 1

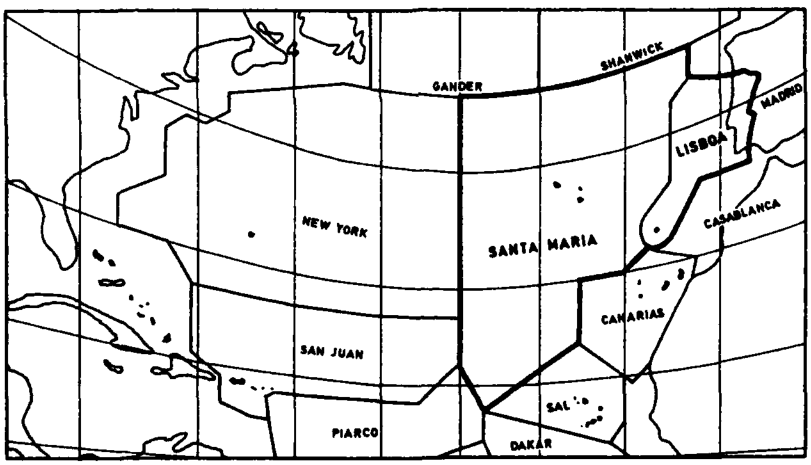

FIG. 1

2. RESPONSABLE AUTHORITIES

Up to 1978, the air traffic services were, as in most of Europe, provided by the Public Administration, through the General Directorate for Civil Aviation - DGAC. At that time, it was found that the existing organization was not able to cope with the urgent need for replacement of systems and concepts,so an executive body - Aeroportos e Navegação Aérea, ANA EP., was set up, with the old DGAC, retaining the regulatory and licensing functions.

Although ANA is now the main authority for the provision of ATS, the law foresees the possibility of other entities providing these services, if so licensed by DGAC.

In fact Air Force is providing Air Traffic Services for commercial civil traffic in one airfield which is simultaneously an Air Base and a civil airport, and the local government in Madeira is showing interest in assumming that same responsability in the airports of Madeira.

Air Force retains full responsability for ATS in air bases and associated airspace.

The present organization is outlined in fig. 2.

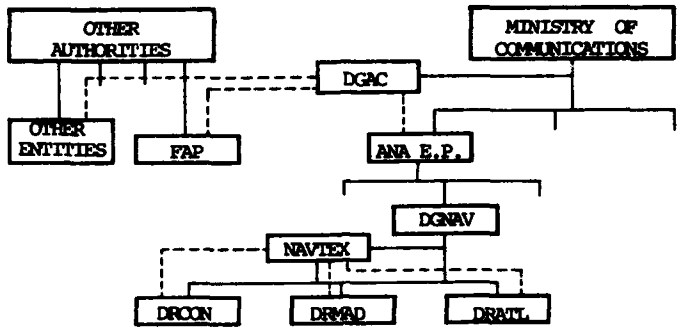

FIG. 2

3. FACILITIES; AN OVERVIEW OF ONGOING DEVELOPMENTS

When ANA was created all the existing facilities were either very old or approaching the limit of their useful life, and a replacement program was urgently needed; two projects were set up, one for the Lisbon FIR, and another for the Santa Maria FIR, code-named NAV I and NAV II.

The developments of these projects was coincident with the begining of the finantial crisis of airline industry, and, in Portugal, with the increase in military activity following the end of overseas operations.

To respond to this situation, study groups were set up with full participation of all the interested parties, to look at the various components of the system:airspace organization, ATS procedures, Navaids, Radar, ATC units, civil-military coordination, cost-effectiveness.

The critical balance of any controlled-airspace, is traffic demand versus ATC capacity; in a situation like ours,where traffic demand is seasonal and tidy, the increase of ATC capacity must be carefully checked against cost, a trade-off beeing necessary between costs and peak traffic delays.

It was our opinion that the best approach to the required "flexible" increase in ATC capacity would be to very carefully analise the controller constraints under peak traffic conditions, and to write down requirements that would relief him from these constraints.

These operational requirements led to a decentralized computer configuration, with a mini-computer at each sector (WPP) for maximum flexibility, and to doubled main--chains with cross-conections for maximum reliability.

The data flow and processing chain of Lisbon Center is presented in fig. 3.

Beeing cost one of our main concerns, a decision was taken to integrate to the maximum extent possible civil and military facilities; this was fully achieved at the Comms, Navaids and Center levels; in radar stations owing to the high level of required reliability, the solution has been to colocate independent civil SSR with the military stations, beeing the information exchanged to both users.

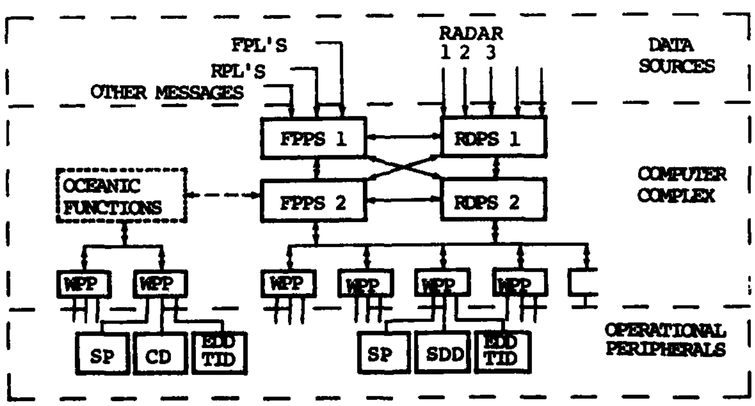

FIG. 3

Finally, in what concerns NAV II, a decision is still to be taken in the required level of automation; it has not been possible to find ways of agreement on common operational specifications for the NAT Region, each state following its own ideas; This is, in our view, a very unfortunate situation,which leads to increased costs and lower level of services for the users, and a situation which should be easily overcome owing to the small number of states involved.

As for the location of the center, ANA had foreseen to transfer it to Lisboa, thus significantly reducing costs, as spare space is available either in the center or in computing capacity; however, following political pressures, a new center will probably be build in Santa Maria.

The NAV I, project, now under implementation, shall be fully operational in the beginning of 1985, with NAV II following one year behind.

AIR TRAFFIC SERVICES IN PORTUGAL

CIVIL-MILITARY COORDINATION ASPECTS

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1. This presentation deals with the provision in Portugal of Air Traffic Services to civil and military aircraft and concurrant procedures. This assessment is based on a strictly military point of view having in account either its requirements or national and international involvements.

All over the world the users of the airspace as well of the Air Traffic Control Systems are basicalli the General Aviation, Air Carriers with their trunk, regional and short haul categories and the military aviation.

The effect that military activity has on ATC Systems is extremely inconstant depending on either airspace structure or Air Traffic Services organization at each country.

Almost of us have the feeling that when a military operational flight takes place, the ATC Services either civil or military must authorize its operation being impossible to refuse it. This feeling comes mainly from two factors:

We have the civil aviation with its financial value but on the other hand the main Air Force task that is its readiness for defence purposes.

For long time only military aircraft flew along upper airspace and slowly civilian aircraft began to invade it.

This means that something had to be shared, either the airspace or the constraints.

However the air defence readiness concept is out of any airspace or air traffic control constraints.

As support of that readiness, our training must be as actual as possible; it means that sometimes we have to schedule missions to the airspace which behaviour and profile cant't comply with provisions of ICAO rules.

Next, we have air defence missions which must be fulfilled without any delay; it means that to do this, only a policy of open airspace to the Air Force will comply with its basic requirements; to this effect only throughout an effective civil military coordination it will be feasible.

On the other hand, national civil authorities have their own air policy, concerning the development of Civil Aviation in the airspace under its responsability, either over the territory or over that committed by ICAO. So, we have that any airspace structure and ATC organization at any Country must provide full protection for civil and military aircraft without to deviate them substancially from optimum or planned flight profiles.

The ultimate objective is, therefore, the provision of adequate separation between all aircraft.

To this effect, in Portugal, as in other NATO Countries, we accept the global definition of two types of Air Traffic:

GAT - <u>General Air Traffic</u>
Flights conducted in accordance with the rules and provision of ICAO.

OAT - <u>Operational Air Traffic</u>
Flights which do not comply with the provisions stated for GAT and for which rules and procedures have been specified by appropriate authorities.

2. AIR FORCE POLICY

In Portugal the mission of the Air Force is to be prepared to intervence, at any time, in the national territory integrity defence, maintaining and improving its dispositive of security and in exercises, alert phases or belligerency status which may occur from international situation as well on other emergency situations where its action becomes necessary to safeguard people and lands.

The mission of the Air Force is established having in consideration its own responsability, the other armed forces shared responsability and the supletive responsability related to different State Departments.

In respect to the first and primary responsability we have to consider combat and attack operations against enemy, air power superiority and the establishment of concerned and available air doctrine.

Next, we have the shared responsability, where our main task is to participate in jointed and/or combined operations in favour of national territory defence.

The supletive responsability regards the participation of Air Force supporting reinforcement operations in benefit of authority of State and civilian protection.

To fulfill with its primary mission, the Air Force:

- Will defend national territory against attacks come from airspace vectors maintaining air superiority.
- Will contribute with forces and support means in benefit of NATO Countries Defence requirements
- etc

It is therefore and so, that will be in the AIR FORCE mission inserted in a National Defense context that the main part of the air national policy will be settled regarding the establishment and activation of any Air Traffic Control System and associated rules and procedures.

Such a policy doesn't comply with any restrictions to Air Force manoeuvering freedom and requires high security level in all flights either on training missions or on combat manoeuvering missions.

So it is deemed useful to establish such an organization which, in peacetime mainly, be able to grant an allotment of facilities in order to:

a. All military flights be conducted in security under any weather conditions and without restrictions to any tactical requirement.

b. Be guaranteed full Air Traffic Services to everyone.

c. Be alerted in due time the Rescue and Coordination Centers.

d. Be fully acquired, processed and disseminated the Air Movement Information in benefit of Air Command and Control System.

3. Civil Aviation Policy

Great part of Air Traffic Services policy in Civil Aviation tends to consider the Airspace as fully open to the Civil Aviation transit either Air Carriers or General Aviation.

4. Discussion

The AIR FORCE accepts the concept that in peacetime the civilian air traffic, mainly the air carriers, having in mind the economic vector, may deserve a prerogative. It means that the Air Force requires high operational freedom but is conscious of Civil Aviation technical requirements in airspace and the high effect in national economy. However, as well known, all we have in peacetime to prepare at all levels our own devices to face the times of crisis, tension and war.

The solution of the problem of compatibility between the two types of air traffic passes by the guarantee of their independence, flexibility and security.

To the provision of Air Traffic Services in a given airspace we can find out few solutions and not almways is easy to adopt the best one.

At NATO Countries civil and military ATS vary from two independent organizations with various degrees of coordination to a complete integration.

5. ATS Civil-Military Coordination Bodies in PORTUGAL

There is a NATO document from Committee of European Airspace Coordination which recommends that member States be invited to continue to examine the problems of civil/military coordination with a view to establish closer coordination between civil and military authorities leading to one ATS system responsive to both civil and military requirements. Since 1957, through agreements we have a valid cooperation with civil authorities, mainly at Lisbon ACC level where we installed a coordination body. In order to increase the coordination aspects the Minister of Transports and the Chief of Air Staff agreed to develop efforts and so a Protocol of Agreement was signed in 1976.

This agreement deals with:

a. Definition and Management of the Airspace.

b. Air Transport

c. Optimization of Air Navigation and Infrastructures

d. Civil protection including the safeguarding against acts of unlawfull interference in Civil Aviation.

e. Utilization of human resources and technical means.

f. Support to basic activities in Aviation encouragement.

Following this Agreement and as first step there is in Portugal a Standing Committee, at inter-ministerial level, whose purpose is to develop cooperative arrangements between AIR FORCE and Ministry of Communications in those areas of common interest to Air Force and Civil Aviation activities (Fig. 1).

On second step the ONCEA, a working-level civil military standing body which operates under the general guidance outlined by the Standing Committee and conducts studies in the establishment, development and implementation of standards and procedures applicable in our Airspace (Fig.1).

Nowadays, on operational and technical organization matters the condination for OAT and GAT flights is provided by a military post in Lisbon ACC (Fig. 2/3/4).

The ongoing ATS Systems renovation project, whose first phase is foreseen to be completed in January 85 will grant a closer civil and military coordination.

In the new system the civil-military cooperation will be built up at Radar Stations, communications and at Lisbon ACC levels. (Fig. 6).

In fact, the new radar coverage will obtained from three stations:

One at Lisbon for TWA Air Traffic control services and the other two stations be installed at Montejunto and at South of Portugal.

The enroute radar stations will have Secondary Radar (SSR) only, although the Montejunto station will receive primary radar data from the military station.

At that time our system will be of the type of collocated operational and technical organization with four military control positions and Supervisor side by side with civil positions (Fig. 6).

The establishment oh these positions corresponds to the model of cooperation choosen and it seems to be the best to solve our problem. To support this system we have efficient Aeronautical Fixed Services (Fig. 4/5).

The airspace will be only one to both types of air traffic and the management of means will belong to civil or military controllers depending of GAT or OAT flights. To solve the joint civil military problems we are evaluating the present airspace structure over Portugal mainland in order to find out a solution.

As you know we are about 55.000 square nautical miles of national territory with two FIR/UIR under our responsability and we have a very limited set of alternatives.

So, our method has been established according to the following steps:

- Evaluation of present airspace structure
- " of airspace structure alternatives
- Identification of national requirements either civil or military in a medium and long term basis.
- Scoring of use of airspace on a cost-efectiveness basis.

The traffic segregation will be reduced to a minimum acceptable and none of civil or military people envolved will loose his own identity being possible to grant the essential mobility to the fullfilment of mission assigned to Civil and Military Aviation. Air Force is trying jointly with Civil Aviation to identify and specify models and methods for optimize the air traffic coordination. This study is a part of Project NAV I which began 4 years ago and is still going until 1985. Besides we have our Air Defence program, known as SICCAP Project with interface with the civil Project.

6. SEARCH AND RESCUE SERVICES

To provide search and rescue services withinthe FIR/UIR's of our responsability we have two Rescue Coordination Centers reesponsible for either promoting efficient organization of search and rescue services or coordinating the conduct of search and rescue operations.

Both Centers are under responsability of AIR FORCE. One is located at Lajes Field in the Azores to Santa Maria FIR/UIR, and the other is under installation at Monsanto to Lisbon FIR/UIR.

Meanwhile Lisbon ACC coordinates SAR services with Air Force Operational Command while military aircraft and other means conduct search and rescue operations.

7. Civil-Military Aeronautical Information Services

The civil aeronautical information publications (AIP, NOTAM, etc) also include the data related to military services and installations that can simultaneously be used by military and civil air trafiic.

We have separated services but a full change of information is established.

8. In Portugal, civil and military authorities , both are doing their best efforts in order to follow a common policy concerning the provision of Air Traffic Services having in account either civil or military requirements in extended national and international context.

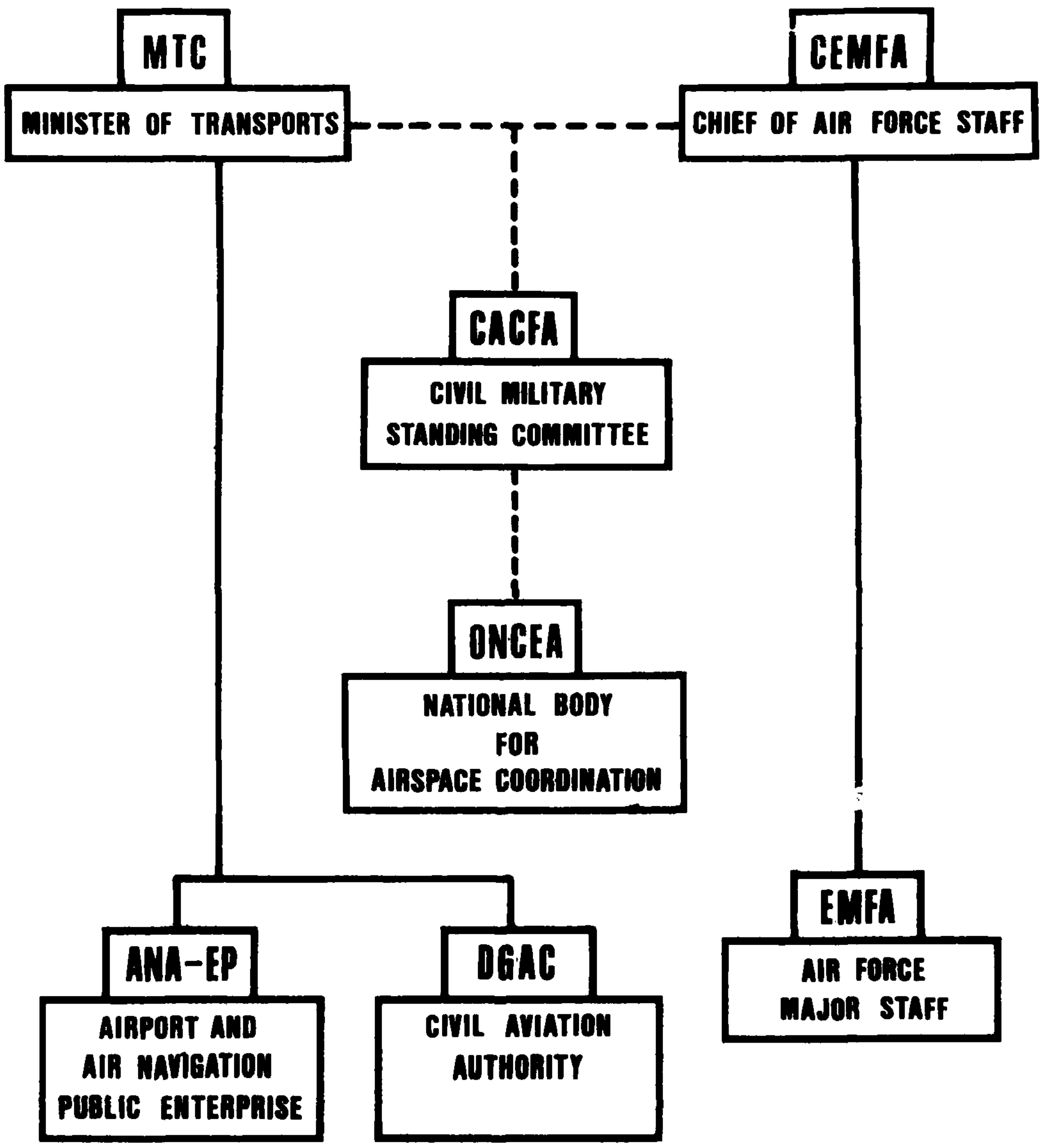

Figure 1

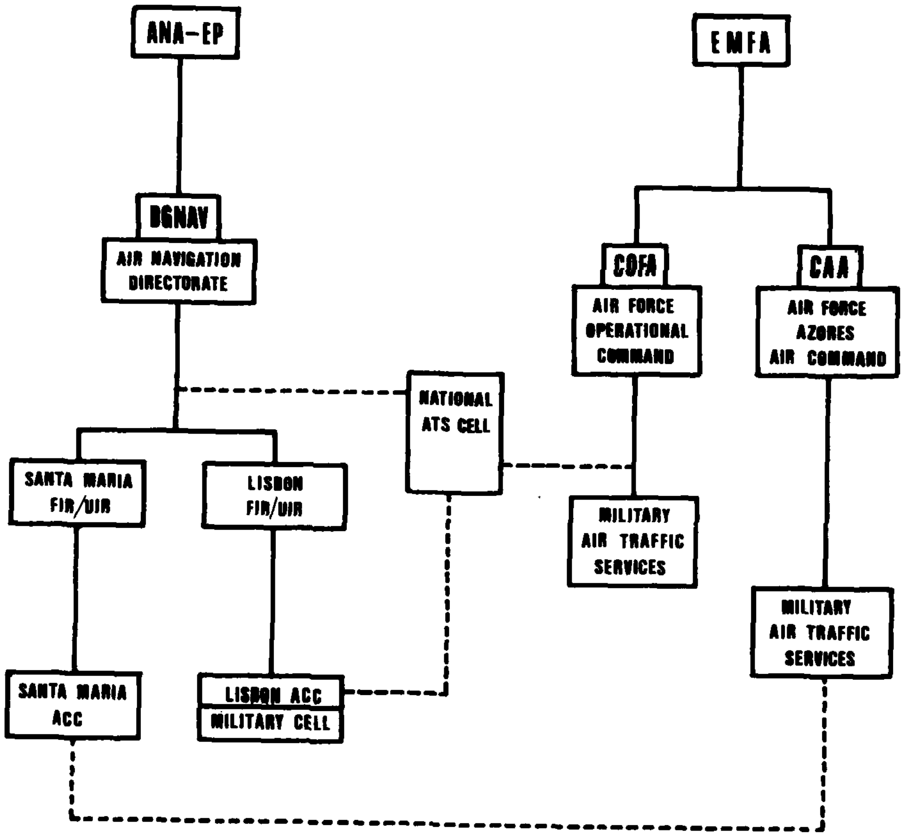

Figure 2

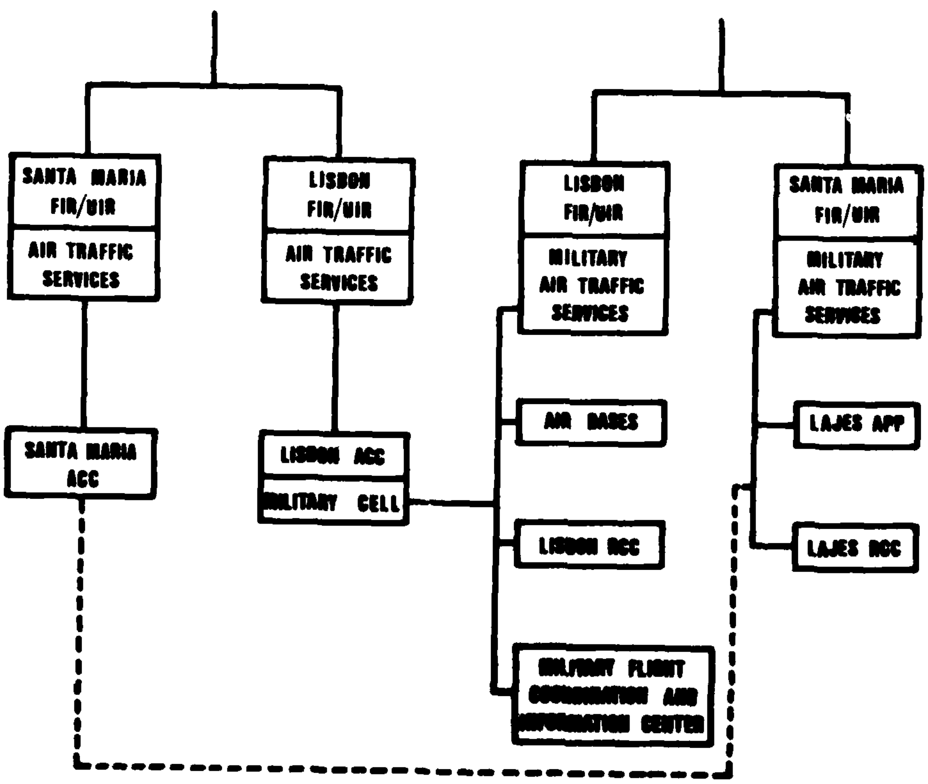

Figure 3

LISBON FIR/UIR
AERONAUTICAL FIXED SERVICES

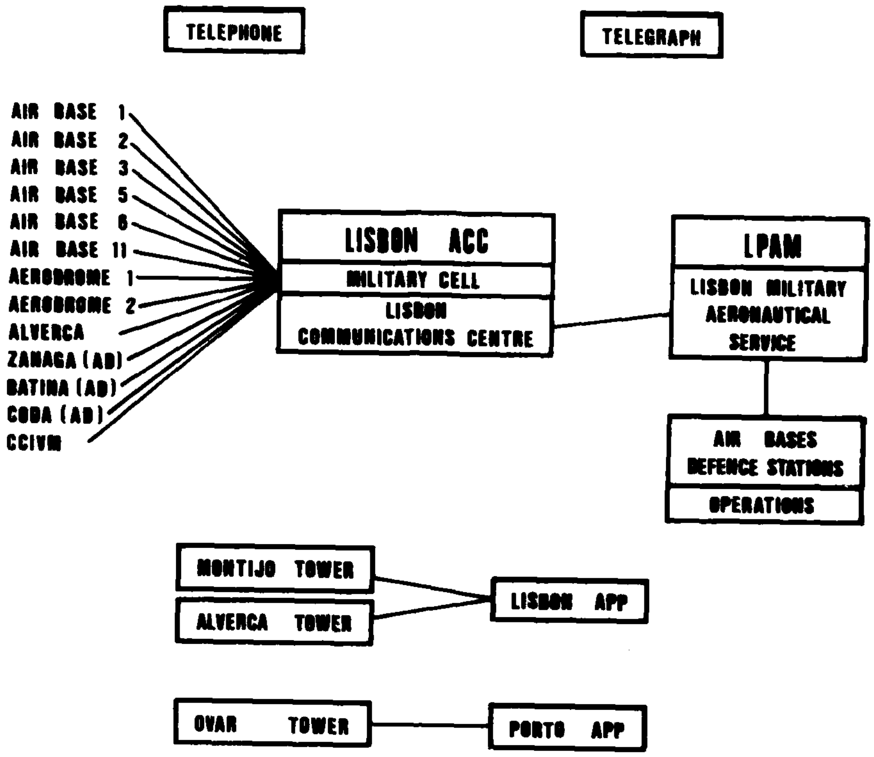

Figure 4

SANTA MARIA FIR/UIR

AERONAUTICAL FIXED SERVICES

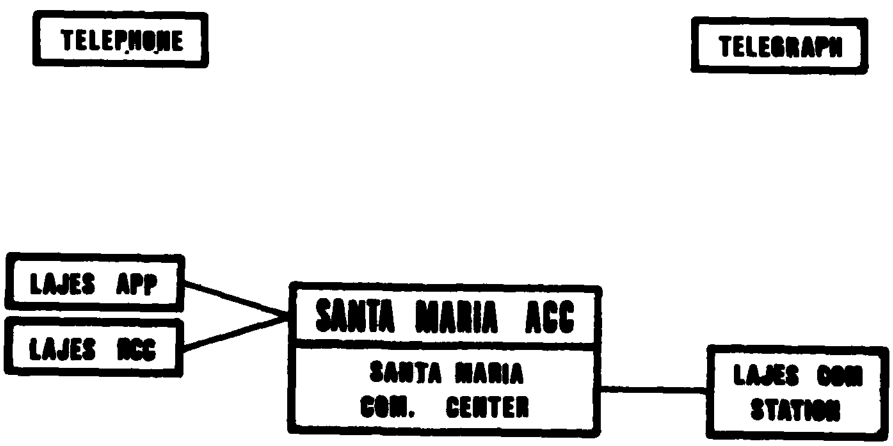

Figure 5

RADAR INFORMATION SOURCES

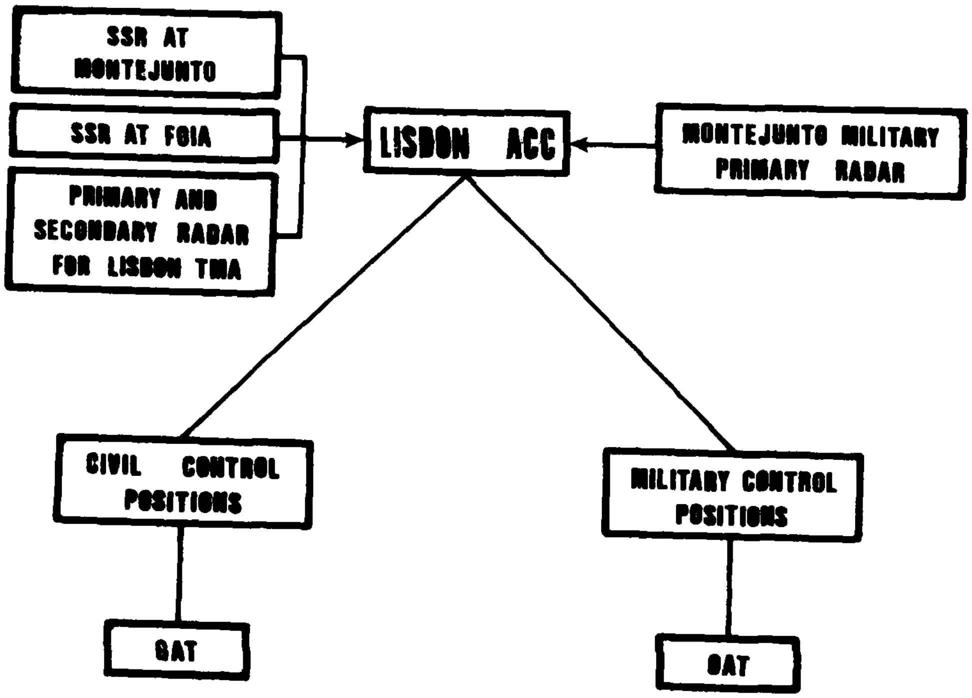

Figure 6

POTENTIAL DEVELOPMENTS AND APPLICATIONS

Introduction by S. Ricciardelli, Session Chairman
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I am honoured to chair this session about potential developments and applications in air traffic control.

I have personally experienced some theoretical and practical efforts in this area, leading a research team involved in a 5-years program, sponsored by the Italian National Research Council.

What really impressed me, from the very beginning, was the managerial dimension of the overall ATC problem, involving a broad scenario of different aspects and various actors with complex interrelations among them.

It is common knowledge that, from a global point of view, safety, efficiency and economy are the objectives to achieve, with safety being of primary concern. Nevertheless, inasmuch as these aspects are so closely interrelated, devising a good solution, suitably covering all three meanwhile taking due priorities into account, appears to be quite a serious task.

Furthermore, ATC is not a self-contained system in what it is subjected to external pressures, which impact, to some extent, the relevant problem. For instance, the significant growth in the U.S. general aviation, gives clear evidence of the importance of market forces as driving forces. Therefore, the ATC role should be carefully considered in the greater context of transport systems.

Focusing only on ATC endogenous factors, it is usually reckoned that a different control philosophy must be pursued in order to gain more efficiency and economy. During the last decade many remarkable papers, about this topic, have been provided by eminent scientists.

In particular, most of them assume that a hierarchy of control loops can be envisaged, such as to associate to each loop a different lead time to predict events and to solve relevant problems.

Since defining the various loops is a controversial point, let synthetically classify them into three main groups:
- long-term planning actions,
- medium-term strategic interventions,
- short-term tactical/procedural control.

In today's air traffic systems short-term interventions, essentially devoted to safety, clearly prevail over medium and long-term interventions, more adequate for expediting and maintaining orderly aircraft flows.

Future developments call for a more extensive use of the latter control techniques, together with introduction of a higher degree of automation, in order to reduce delay times and operational costs by making best use of system capacity or by attempting to increase present capacity.

As far as long-term planning actions are concerned, Ratcliffe lays emphasis on the need to carefully define the planning time scale. In fact, he asserts that it is not convenient to concentrate research and development when future is fairly too uncertain to make predictions or when it is so near that no appreciable influence can be exercised.

Moreover, implementation of long-term plans and developments is quite a delicate matter. Owing to changing environment, human factors and time necessary for technology improvement, reconfiguring the system in a gradual, evolutionary way is more likely to account for reliability than a "clean sheet" approach, involving drastic changes.

As regards medium-term interventions, let confine attention on the strategic control concept within a "zone of convergence", which is an area sufficiently large so as to guarantee a level of control able to make aircraft fly almost uninterrupted climb/descent trajectories.

Particularly, Benoît and Swierstra have performed remarkable studies and experiments in this field, supported by Eurocontrol organisation. Other valuable research efforts and tests, along these lines, have been conducted by qualified experts of F.A.A., Royal Radar Establishment and other institutions.

In general, beyond different emphasis placed on various aspects, practical implementation of strategic control aims at gaining capability of flying pre-planned conflict-free paths, which can be arranged to be economic.

This requires advanced 4-D trajectory prediction, monitoring and updating, with pilot carrying out a set procedure. In addition, future progress to augment stategic control ask for further development in airborne navigational aids and, in general, for modernising current airway and ground facilities. As a consequence, a joint effort both on the conceptual and the technological side will, positively, contribute to fuel savings and delay reduction.

Notwithstanding, ATC has to deal with users community, which is also claiming for other issues like workload constraints, division of responsibilities, coordination and, more generally, noise and pollution.

Thus, any system design must include a wide range of customers to satisfy: airlines, general and military aviation, all ATC system operators, air transport users and even municipal and national administrations.

In closing, let me state that, in my opinion, improvement in quality of air traffic services needs to enhance cooperation up to synergy among all different bodies concerned with ATC.

OVERVIEW OF UNITED STATES PROGRAM FOR MODERNIZING AIR TRAFFIC CONTROL AND AIRWAY FACILITIES

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SUMMARY

The Federal Aviation Administration (FAA) recently completed a comprehensive plan for modernizing the United States (U.S.) Air Traffic Control and Airways Facilities over the period from now to the year 2000. This paper provides an overview of this plan and describes some of the recent technological developments that provide the foundation for significant improvements to the system. These improvements include a new discrete address surveillance and data communications system, an airborne collision avoidance system that operates independently from the ground-based air traffic control system, the replacement of the air traffic control computer facilities with modern equipment, the inclusion of a higher level of automation to aid the controllers and to provide greater freedom of flight, precision landing aids using microwave equipment, and enhanced dissemination of severe weather information to controllers and pilots. Other innovations are also planned in order to meet an increasing demand for air traffic control services but without incurring a proportionate increase in the cost of providing these services.

INTRODUCTION

The Federal Aviation Administration (FAA) has recently completed a plan covering the next 20 years of modernization of the Air Traffic Control and Airways Facilities in the United States. This plan, the National Airspace System (NAS) Plan, has resulted from 10 months of extensive review of the present and future expected demand for FAA services, of the design of our present system, and of potential design improvements. New technologies were carefully examined to take full advantage of potential functional and performance improvements, providing that the risks did not appear to be excessive during this 20-year time period. A description of the major elements of this plan follows, with some detail of the new techniques and technologies which are part of it.

The plan is comprehensive. It covers all major elements of the FAA facilities which relate to air traffic control. Figure 1, which lists the chapters of this plan, demonstrates its scope.

Motivation for upgrading the system is summarized by Figure 2. A primary motivation arises from the expectation that demand for services from all segments of aviation will increase significantly over the next 20 years. In addition, recognizing that the present system is labor-intensive, satisfying the demand would be costly if the present configuration is simply expanded. Not only would direct expansion of the present system not solve the problem, but also the present system is based on aging equipment which, if not replaced, would represent a major and growing operating cost. This fact alone would justify upgrading the system, even if the expected growth in demand does not materialize.

GROWTH IN DEMAND

Figure 3 illustrates the forecast aviation activity for approximately the first half of this planning period. Only the civil aviation activity is depicted by this Figure, and is expressed in terms of passenger miles flown for the air carrier and commuter aviation, and in hours flown in the case of general aviation and helicopters. Clearly, significant growth is expected in each of these segments, and in aggregate.

Perhaps a more relevant picture is suggested by Figure 4, where the demand is expressed in terms of services required at FAA facilities, towers, and flight service stations. Although not shown, a similar picture exists for operations using other FAA facilities, particularly en route and terminal control facilities. New kinds of service demands are also expected. In particular, helicopters are expected to increase operations under instrument flight rules and in airspace set aside for their use in order to maximize fuel efficiency. Further, helicopters will use airspace that may require new communications, navigation, and surveillance methods because of their low altitudes of operation. These include operations to offshore areas, remote areas, and into city centers.

While recognizing this expected growth, the FAA must also consider some practical limitations. One of the most significant is that of airports and runways. It is unlikely that any major new airports will be constructed during this period. Therefore, the number of runways available for larger aircraft is probably limited to what exists today. Consequently, system capacity improvements must result from upgrading efficiencies of operation, especially through the employment of higher levels of automation.

MAJOR DECISIONS

The NAS Plan embodies a number of critical decisions regarding the future course of the evolution of air traffic control. The following discusses the principal decisions.

There have been numerous suggestions that certain ATC functions be delegated to the cockpit. A basic decision is the first one listed in Figure 5. Although the delegation of additional ATC functions to aircraft appears to be technically feasible because of the availability of new technology, there is insufficient evidence that doing so would be operationally successful or beneficial. Traffic information, for example, can be made available to the pilot either via the data link service of Mode S or by the onboard traffic

alert and collision avoidance system, both of which are discussed later in this paper. This information could be used to present to the pilot a plan view display of nearby traffic. However, the basic question of whether pilots of several aircraft so equipped with such displays can maintain self-separation has not been answered. Until this has been safely demonstrated and significant benefits identified, the FAA believes that centralized control, embodied in an air traffic controller on the ground, will continue to be required to maintain safe separation and ensure a smooth flow of air traffic.

The next decision listed in Figure 5 relates to the introduction of new systems to improve the efficiency of different elements of the FAA operations. Basic to all of these is automation, or the use of equipment to augment human capabilities. This will be expanded on subsequently in this paper.

Figure 5 next shows that the FAA will implement the new Microwave Landing System, or MLS. This will be accomplished over a period of years where MLS will initially be a supplement to the Instrument Landing System (ILS) to aid in the transition process.

As mentioned earlier, automation to augment human capabilities is a theme that is followed in the plan. Another area where automation will be applied relates to weather observations. New technology, now available commercially, will be applied to the function of station observations. New weather radars which will measure wind and turbulence by Doppler techniques will also be put into the system. These observations will be disseminated throughout the system to provide realtime data to both controllers and pilots.

The next major decision relates to upgrading airport capacities. This is not a new decision but a reaffirmation of the continuing need to operate the system as efficiently as possible to accommodate the traffic growth with essentially a fixed inventory of runways.

On the next point, today's system has 25 air route traffic control centers and 184 automated terminal facilities. These as shown on Figure 6 will be consolidated into a total of 60 facilities: en route facilities will pick up the responsibility for some of the terminal operations within the center area; some new facilities will be created to control the traffic in a number of contiguous or nearly contiguous metropolitan airports. Similarly, today's 317 flight service stations will be brought together into 60 automated flight service stations. Flight service stations are the principal source of weather and flight planning information for the general aviation pilot. Whereas much of this service is provided today to the pilot directly at the flight service station, at the new facilities it will be almost entirely by telephone.

There will also be a consolidation of the technical facilities, providing communication, navigation, and radar services.

This planned consolidation should be kept in mind as we examine some of the changes planned for the elements of the system.

As stated earlier, key to the desired improvement in efficiency of the FAA operations, as shown in Figure 7, is the introduction of higher levels of automation into the control process. This goes hand in hand with the introduction of a new computer system for both terminal and en route control. Recognizing the time necessary for such a major change, the presently planned upgrading of the current terminal control systems (ARTS II and III) will proceed, and the initial implementation of the new computer system will be in the en route traffic control centers.

This new, common terminal and en route computer system will allow the gradual introduction of higher levels of air traffic control automation, providing for a comprehensive management of the overall air traffic flow.

In addition to the automation of the traffic control centers, substantially greater levels of automation will be introduced into the flight service operations, making information much more readily available to the flight service specialists and also making this information available to pilots directly from remote data terminals via telephone data communications. The expected result of these changes is that about 70 percent of the services rendered today by flight service station specialists will be replaced by direct access to the computer data base. Expected growth in demand will therefore be accommodated without an increase in staffing. Preflight access to the weather data base will be accomplished either by remote terminals or by computer-generated voice responding to inquiries made on touchtone telephones. This will provide information on various weather products, NOTAMs, and will allow for the automatic filing of flight plans.

The final area of major systems decisions, shown in Figure 8, relates to air traffic surveillance and separation. Key to this is the decision to implement Mode S as an evolutionary upgrading of the current Modes A and C secondary surveillance radar. Using Mode S, aircraft will be addressed discretely by the ground system, allowing for the interchange of data link messages between ground and aircraft, thus providing a new air-ground communication capability to supplement voice. This same signalling capability will be employed for air-to-air communications between TCAS-equipped aircraft for traffic alerts and for coordinating conflict resolution maneuvers.

As part of the planned upgrading of the secondary surveillance radar system, it is anticipated that en route primary radar will be phased out by the year 2000. Terminal primary radar will be retained with an upgraded weather capability, and a new multi-function weather radar system will be provided for en route weather information.

At this time the use of the air-ground data link has not been fully defined. The FAA plans to make available a variety of data link services in incremental steps as requirements are firmed up. Initially, the link may be used to make weather information more easily available to the pilot in flight. Early air traffic control functions under consideration would include the automated sector handoffs and clearance delivery.

Another data link function under consideration is the automation of the ground-based radar traffic advisory service. This can provide to the Mode S-equipped aircraft an equivalent traffic advisory service to that provided manually, without, however, loading the air traffic controller.

A key decision with regard to separation is the early introduction of an airborne traffic alert and collision avoidance service, or TCAS, totally independent from the ground. This service will provide a backup to the air traffic control process, providing the pilot of the equipped aircraft with timely warnings if the ground-based system fails to provide adequate separation, and a maneuver command to ensure safe resolution of a conflict. TCAS parameters are set such that controller actions, aided by conflict alert and conflict avoidance functions, will normally precede TCAS commands. TCAS, therefore, is a backup to the ground system actions.

COMPUTER MODERNIZATION

Let us look now in greater detail at the planned modernization of the air traffic control computer facilities. Figure 9 indicates that with currently planned improvements, these facilities are adequate to handle the demand of the next several years. However, it is recognized that both to accommodate future demands and to eliminate the increasing costs associated with maintaining aging equipment, a replacement computer system is required. Current computer technology is adequate to the need. The issue is the system design or overall architecture. As pointed out earlier, merging of the en route and terminal functions is expected to provide increased efficiencies both in realization of the system as well as in its operation and manning.

Figure 10 shows that the implementation of the new computer system will proceed in three major steps. First, new hardware will be introduced which can accommodate the existing software and display consoles or sector suites. Second, new system software will be introduced simultaneously with new sector control suites which have substantial integral computation capability. Finally, with the expansion of the processing capability provided by the new sector suites, software embodying higher levels of automation, including automated en route air traffic control, or AERA, will be introduced.

To see what this means from the controller's point of view, compare Figures 11 and 12. Figure 11 depicts the typical current sector suite, manned by three or four controllers; the radar controller assisted by others to handle bookkeeping and coordination functions.

The present concept for the new sector suite is shown in Figure 12. With the assistance of the increased levels of automation, one controller can perform the functions which previously required several.

The introduction of the new sector suites will allow a number of functional improvements in the air traffic control process, as depicted by Figure 13. The near-term will include expanded conflict alert and resolution capabilities, more convenient displays, the introduction of DABS, or Mode S, data link capabilities, and more convenient access to weather information. In the longer term, the expanded functions of AERA will be introduced, including en route flow management and strategic clearance planning, and tactical clearance generation allowing for the much more widespread use of direct, fuel-efficient routes.

WEATHER

Let us turn now to look at the planned upgrading of weather facilities.

The principal requirements, shown by Figure 14, are for improved and expanded services and, simultaneously, lower cost. Real-time weather information should be more readily available, both to pilots and controllers, at an increased number of reporting points. Many airports today at which instrument flight operations take place do not have weather reporting facilities.

Figure 15 depicts the overall architecture of the automated weather system. The core of this is the center weather processor and the center weather service unit. These units accept inputs from weather radars and, via flight service stations, from manual and automatic weather observations, and provide data to the terminal and en route controllers and, again via the flight service station data processing system, to the automated flight service stations.

Key to this system is the introduction of automatic weather observation systems. These will replace human observers at many terminal facilities, automatically providing observations of wind direction, velocity, altimeter setting, temperature, dewpoint, ceiling, and visibility.

Not only will this information be available through the centralized automated weather system, but it will be broadcast locally to make the information available directly to the pilot, as shown on Figure 16. Not only will he be able to get information from these local automatic weather observation systems, but also via the Mode S request/reply link. The pilot in flight will be able to get any of the weather products stored in the center weather processor, thus providing substantially more convenient weather information availability.

MICROWAVE LANDING SYSTEM

The introduction of the microwave landing system, already developed through an extensive international cooperative process, has been made an element of this plan. The key motivating factors for the introduction of MLS are listed in Figure 17. They include: its reduced site sensitivity, allowing its use at many airports which cannot economically accommodate ILS; a larger number of channels permitting use at more closely spaced

terminals; increased guidance accuracy, especially at difficult sites, providing the basis for expansion of category 2 and category 3 services; and the provision of precise guidance over a wide coverage area, allowing the use of many approach paths and affording precision departure and missed-approach guidance as well as approach guidance.

Figure 18 illustrates the principal features of the microwave landing system, emphasizing that it is an air-derived system and provides precision guidance in azimuth, elevation and range. Elevation and azimuth guidance are provided at C-band, or roughly 5000 MHz, whereas the distance, or DME, function is provided at L-band for compatibility with existing L-band DME.

The MLS coverage volumes are depicted in Figure 19 which emphasizes the ability to use other than straight-in approach paths, various glide slope angles and precise departure guidance as well as approach guidance.

MODE S

A key element of air traffic control automation is the introduction of Mode S, or discretely addressed secondary surveillance radar. First of all, as shown on Figure 20, Mode S will provide improved accuracy and continuity of air traffic surveillance, enhancing the ability to track, and thus project the future position of aircraft, and forming the basis for improved automatic conflict detection and avoidance services. Secondly, Mode S provides the ground-to-air and air-to-ground data link on which many of the future automated air traffic control services depend.

While the full benefit of Mode S depends upon both the ground facilities and aircraft being equipped, much of the surveillance improvement is obtained just by the introduction of monopulse techniques and improved signal processing at the ground-based interrogator facility. In fact, some administrations are moving forward to introduce this capability into existing SSR systems prior to the introduction of Mode S.

Figure 21 depicts the improvement in surveillance capability which the new techniques provide. On the left we see the successive aircraft positions determined by a contemporary high-grade SSR system. Each symbol represents a measurement of aircraft position at a 4-second scan period. While this quality of information is adequate for manual control, it represents a quite noisy input to a tracker and makes difficult the job of projecting future aircraft positions. On the right is shown the same set of aircraft tracks as measured by a Mode S sensor. As is evident, there is much less measurement noise and fewer false targets. This higher quality surveillance data can provide much better projection of future aircraft position, enhancing the performance of conflict detection and resolution algorithms.

As mentioned earlier, there has not yet been any firm decision as to the data link services which will be provided by Mode S. Principal candidates for early implementation, shown on Figure 22, are weather information, traffic advisories, enhanced terminal information service, and air traffic clearances. For the past couple of years, the FAA has been carrying out experiments to determine the utility of some of these services to the pilot of an aircraft in flight. The next few Figures show examples of some of these services, as the information might be displayed in the cockpit.

Figure 23 depicts ground-derived weather information transmitted to the aircraft and displayed on a color cathode ray tube display indicator in the cockpit. For convenience in these experiments, we have used the indicator of a currently available alphanumeric airborne weather radar display. In this display each symbol represents the intensity level of the greatest return in a 22-mile square, with the map centered on the indicated VOR station--in this case, the Oklahoma City VOR. A fairly large area is shown, approximately 200 by 600 nautical miles. As can be seen here, there is a broad area of measurable precipitation with level four returns in one area, indicating a high probability of severe weather in that location.

The same display is shown on Figure 24 depicting the enhanced terminal information service for the Atlantic City airport, giving cloud cover conditions, visibility, surface winds, the approaches in use, and relevant airport information.

Finally, a number of experiments have been carried out to provide aircraft in flight with automatic traffic advisories. Figure 25, on the same display we have seen in previous Figures, depicts the traffic situation with own aircraft in the center, a 2-mile range ring, two aircraft which represent no threat, and one aircraft 400 feet below own aircraft which is judged to represent a threat. For this threatening aircraft, its projected flight path for the next 40 seconds is also depicted.

These data link services, it must be emphasized, represent experiments which have been carried out, not operational services. Much work remains to be done in determining the exact nature of the services, the information to be transmitted, and the character and formats of the displays.

TCAS

The final subject for detailed discussion is the traffic alert and collision avoidance service, or TCAS. Figure 26 lists the major goals of this program.

The desirability of an airborne collision avoidance system, operating completely independently of the ground-based air traffic control system, has long been recognized. Several candidate systems have been developed and proposed for operational implementation. All, however, have suffered from the severe drawback that they provided protection only against other aircraft which were also equipped with compatible equipment. Since it was judged impractical to require all aircraft to carry special equipment for collision avoidance, no such system was ever judged suitable for operational implementation.

TCAS substantially resolves this problem by providing protection not only against other TCAS-equipped aircraft, but also against all SSR-equipped aircraft. Fully cooperative conflict detection resolution is provided when both aircraft are equipped. When one is only SSR-equipped, the burden for conflict resolution falls entirely on the TCAS-equipped aircraft. TCAS has been designed to operate in the highest predicted density air traffic environments expected in the next 20 years, and its interrogations, power levels, and protocols have been selected so as to not interfere with the ground-based air traffic control interrogators. Not only must it not interfere with the air traffic surveillance, but its conflict detection and resolution algorithms must not interfere with normal air traffic control operations; that is to say, this system must not interfere with normal air traffic flow.

TCAS operates in three different ways, as shown on Figure 27, depending on the equipage of the threatening aircraft. If both are equipped with the full capability, or TCAS-II system, they detect each other, automatically coordinate on avoidance maneuver, and display the maneuvers to the respective pilots.

If the detected aircraft is equipped with the more limited TCAS-I, that is with a Mode S transponder and display, the decision on how to resolve the conflict is made solely by the TCAS-II equipped aircraft, and this decision is communicated to the TCAS-I aircraft via the Mode S data link. This allows the same capability for cooperative conflict resolution as in the case when both aircraft are TCAS-II equipped.

Finally, if the detected aircraft is only equipped with SSR, the TCAS-II equipped aircraft cannot communicate its intentions to that aircraft, but must resolve the conflict entirely on its own. Although, as will be pointed out later, TCAS includes an option of displaying the relative bearing of the threatening aircraft, all avoidance maneuvers are vertical; that is to say, climbs or descents.

As referred to in Figure 27, there are three principal versions of TCAS. In Figure 28, the so-called baseline TCAS, formerly called BCAS, has the principal functions of TCAS-II, but a more limited traffic-handling capability.

TCAS-II performs directional interrogation to enhance its ability to operate in high traffic densities, and measures the relative bearing of nearby aircraft for display to the pilot.

The simpler TCAS-I version is primarily intended as a low-cost unit for general aviation. It receives and displays the maneuver intent information from a TCAS-II aircraft, and can provide a simple proximity warning of a nearby SSR-equipped aircraft; that is, it will alert the pilot that there is another aircraft within a few miles of him which he should be looking for, but does not provide information on bearing or altitude, and does not provide a conflict-avoidance maneuver.

TCAS-II provides a display of nearby aircraft similar to that provided by the automated traffic advisory service described earlier. Shown in Figure 29 is an experimental display, displaying the relative bearings and altitudes of three nearby aircraft as measured and displayed by TCAS-II. One, judged to be a threat, is shown in red; that is, the one which has led to the generation of a maneuver command.

IMPLICATIONS TO USERS

Up to this point the paper has focused primarily on planned changes to the ground systems, with reference to related airborne changes. In concluding, the following discusses briefly the implication of these changes to the users of the airspace, the aircraft operators and pilots.

A number of direct benefits will accrue to the airspace users, as shown on Figure 30. A very important one is increased safety: through improved separation services, provided by the ground system augmented by an independent airborne backup system; through improved information on the weather both en route and terminal; and, although not shown on the Figure, through improved landing guidance. Many airports that do not now have precision approach guidance will get it with MLS, and airports which now have ILS will have improved service.

The introduction of higher levels of automation into the air traffic control process, leading finally to AERA, will result in more efficient traffic flow, in turn leading to reduced delays and correspondingly reduced fuel consumption. This comes about both from generally more efficient and predictable operation, and from being able to accommodate much more direct point-to-point operation, rather than requiring conformance to the structured airways as is generally required today.

Most of these benefits, particularly the latter ones related to the automation of the air traffic control process, will not require changes in the aircraft onboard equipment. They will, however, allow the operator to derive greater benefit from sophisticated area navigation and flight management systems with which many new aircraft are equipped.

Some of the new services, particularly those relating to separation and MLS, will require new equipment on board the aircraft. In particular, the TCAS equipment will be required for all operators desiring the enhanced safety afforded by an autonomous, airborne, collision avoidance system. This equipment includes a Mode S transponder and thus, once installed, makes available in the aircraft the other services which will be available on the Mode S data link.

Aircraft not requiring the full TCAS capability can equip with a lower cost TCAS-I or Mode S transponder with appropriate display to realize the benefits of the Mode S data link services, including the automatic traffic advisory service.

Of course, to take advantage of the proliferation of microwave landing systems on the ground will require new airborne equipment.

Finally, meeting the communication needs of the expanding air traffic control system, particularly during the interim period prior to widespread use of data link, will require the increased number of communications channels made available by 25 KHz channel spacing.

In addition to the above direct benefits, an indirect but no less real benefit to the airspace users results from the reduced cost of operation of the FAA that will ensue from the more widespread automation. There has been increasing pressure in the United States to fund a significant part of the cost of operating the air traffic control system through direct user charges. To the extent that this happens, any reduction in system operating cost thus accrues to the user as a direct benefit.

CONCLUSION

As stated at the beginning of this paper and as illustrated throughout, the Federal Aviation Administration has developed a comprehensive plan for the upgrading of the United States air traffic control system over the next 20-year period. Detailed development and implementation efforts are now underway to carry out this plan.

\# \# \#

STRUCTURE OF THE PLAN

CHAPTER	TITLE
I	OVERVIEW
II	DEMAND ON THE SYSTEM
III	EN ROUTE SYSTEM
IV	TERMINAL SYSTEM
V	FLIGHT SERVICE SYSTEM
VI	GROUND-TO-AIR SYSTEM
VII	INTERFACILITY COMMUNICATIONS
VIII	AUXILIARY SYSTEM

Figure 1

PRINCIPAL MOTIVATING FACTORS

- GROWTH IN DEMAND
- COST
- SIMPLE EXTENSION OF PRESENT SYSTEM ARCHITECTURE WILL NOT YIELD NEEDED BENEFITS
- EXISTING FACILITIES ARE AGING

Figure 2

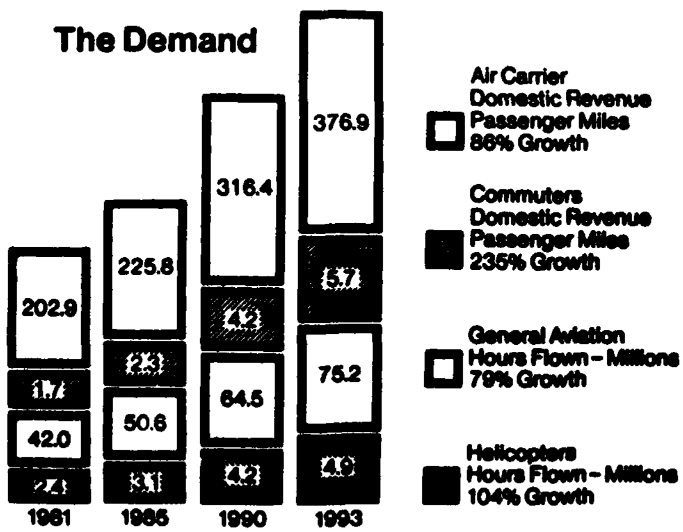

Figure 3

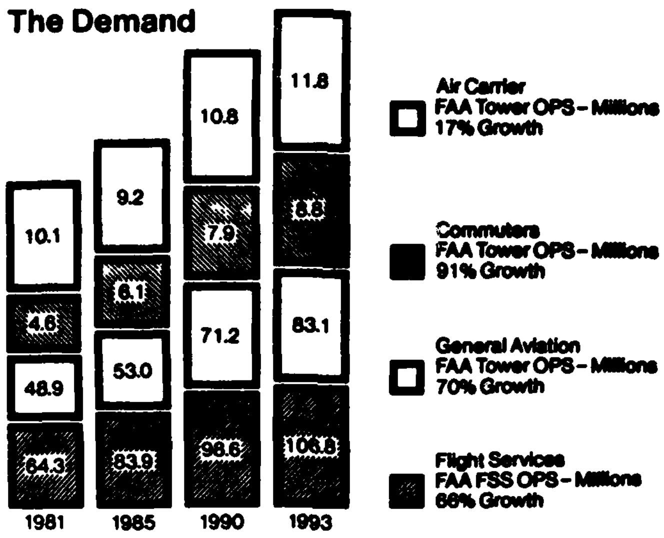

Figure 4

The Major System Decisions

GENERAL

- ATC Will Continue to Be a Ground-Based System
- A Major Improvement of the FAA Communications System Will Be Implemented
- ILS Will Be Supplemented *By, and Then Replaced* By MLS
- Work Must Continue on Improvement of Airports and on Achievement of Higher Airport Capacity
- FAA Will Proceed With Consolidation of Facilities to Achieve Productivity Improvements and Realize System Efficiencies
- Automatic Weather Observation Systems Will Replace Manual Observers

Figure 5

The Facility Locations

Approximately

25 En Route Centers → **60 Facilities**
184 Automated Terminal Facilities → **60 Facilities**

317 Flight Service Stations → **60 FSS's**

3 Major Data Switching Centers → **2 Comm Centers**

3187 Technical Facilities Locations → **1840 Facilities**
Communications
Navigation
Radar

Figure 6

THE MAJOR SYSTEM DECISIONS

AUTOMATION

- FAA WILL PROCEED WITH UPGRADING OF ARTS II AND ARTS III
- A COMMON COMPUTER SYSTEM FOR BOTH TERMINAL AND EN ROUTE APPLICATIONS WILL BE PROCURED
- THE HIGHEST PRACTICAL LEVEL OF ATC AUTOMATION WITH AN INTEGRATED FLOW MANAGEMENT PROCESS WILL BE IMPLEMENTED
- THE AUTOMATED FLIGHT SERVICE STATION SYSTEM WILL BE IMPLEMENTED. MAJOR IMPROVEMENTS IN WEATHER SERVICES TO USERS WILL BE PROVIDED

Figure 7

THE MAJOR SYSTEM DECISIONS

SURVEILLANCE AND SEPARATION

- MODE S WITH DATA LINK WILL REPLACE THE ATC RADAR BEACON SYSTEM
- EN ROUTE PRIMARY RADAR WILL BE PHASED OUT BY 2000 TERMINAL PRIMARY RADAR WITH A WEATHER CHANNEL WILL BE CONTINUED
- TCAS WILL BE AN INDEPENDENT SYSTEM
- AN AUTOMATIC TRAFFIC ADVISORY SERVICE MAY BE DEVELOPED FOR LIMITED TERMINAL APPLICATION
- A NEW WEATHER RADAR SYSTEM WILL BE PROVIDED TO COMPLEMENT TERMINAL RADAR WEATHER CHANNEL

Figure 8

COMPUTER MODERNIZATION

IMPORTANT FACTORS

- CURRENT SYSTEM COMPUTER CAPACITY IS SUFFICIENT THROUGH MID-1980's WITH CURRENTLY ON-GOING IMPROVEMENTS
- AVAILABLE COMPUTER TECHNOLOGY IS NEEDED TO PROVIDE FLEXIBILITY TO ACCOMMODATE THE RANGE OF FACILITIES, CAPACITIES, AND FUNCTIONS PROJECTED
- USE OF DISTRIBUTED COMPUTERS AT THE CONTROLLER POSITIONS WILL PROVIDE NEEDED FLEXIBILITY AND RELIABILITY
- TECHNOLOGY IS NOT A PROBLEM — SYSTEM DESIGN IS
- MERGING OF EN ROUTE AND TERMINAL FUNCTIONS IS NEEDED AND BENEFICIAL

Figure 9

COMPUTER MODERNIZATION DECISION

- REPLACE COMPUTER HARDWARE — (STEP 1)
  - KEEP PRESENT DISPLAYS AND SOFTWARE
- NEW SYSTEM DESIGN — (STEP 2)
  - NEW SYSTEM SOFTWARE
  - NEW SECTOR CONTROL SUITE
  - BUILDS ON ABOVE COMPUTER HARDWARE
- FUTURE AUTOMATION — (STEP 3)
  - AUTOMATED EN ROUTE ATC (AERA)

Figure 10

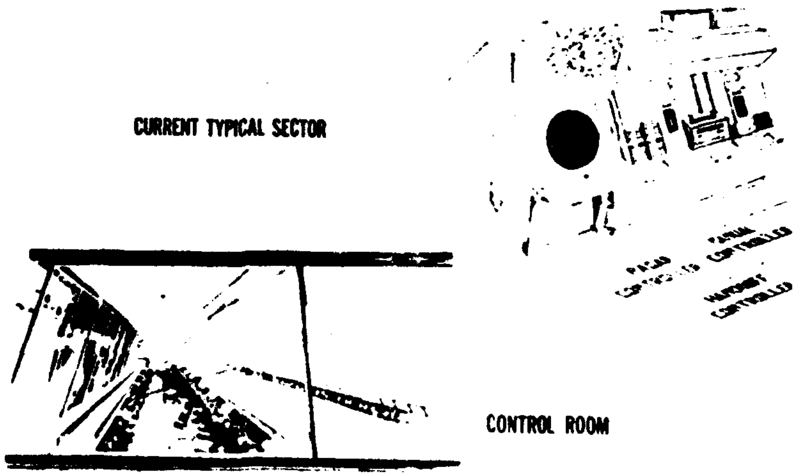

Figure 11

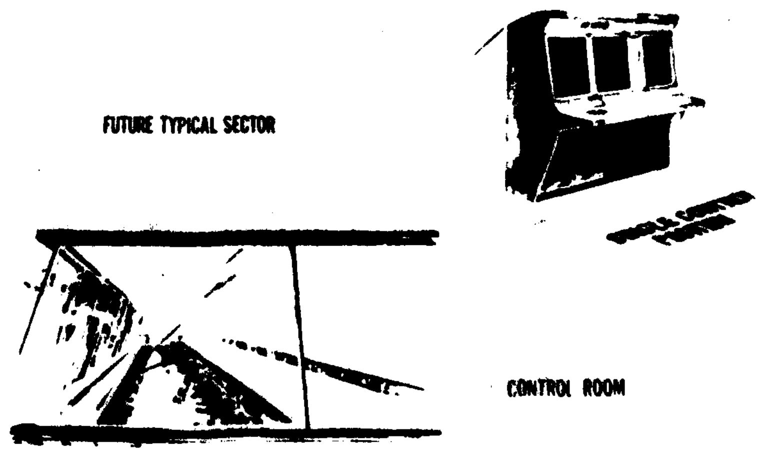

Figure 12

FUNCTIONAL IMPROVEMENTS

- NEAR TERM
  - (1) CONFLICT ALERT FOR VFR INTRUDERS (CA VFR)
  - (2) CONFLICT RESOLUTION ADVISORY (CRA)
  - (3) EN ROUTE METERING (ERM)
  - (4) EN ROUTE TABULAR DISPLAY SYSTEM (ETABS)*
  - (5) DABS INTERFACE
  - (6) CENTER WEATHER SERVICE UNIT (CWSU) INTERFACE
  - (7) TERMINAL INFORMATION DISPLAY SYSTEM (TIDS) INTERFACE
- LONG TERM
  - (8) DIRECT/FUEL EFFICIENT EN ROUTE PLANNING
  - (9) FLOW PLANNING AND TRAFFIC MANAGEMENT
  - (10) STRATEGIC CLEARANCE PLANNING
  - (11) FULL TACTICAL CLEARANCE GENERATION AND EXECUTION

* INCLUDES AUTOMATED "D" POSITION PLANNING FUNCTION

Figure 13

WEATHER

REQUIREMENTS

- PROVIDE REAL-TIME WEATHER TO PILOTS AND CONTROLLERS
- CONSOLIDATE PILOT SERVICES
- PROVIDE OBSERVATION AND REPORTING AT MANY NEW LOCATIONS
- MINIMIZE COST

Figure 14

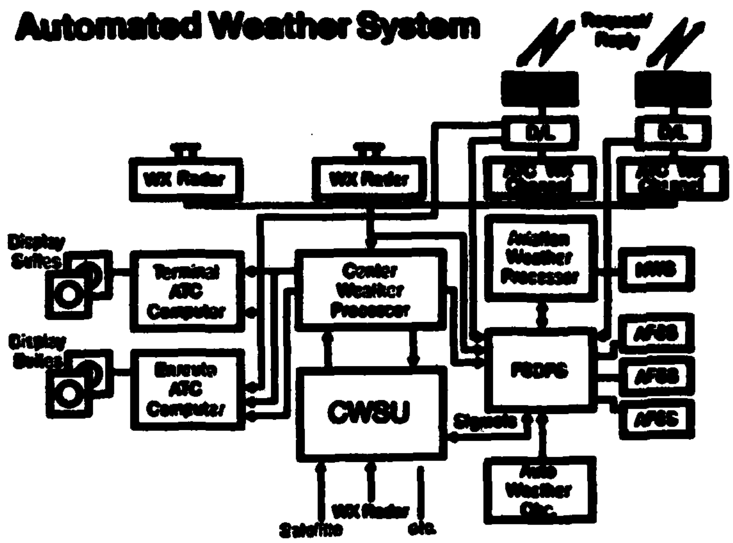

Figure 15

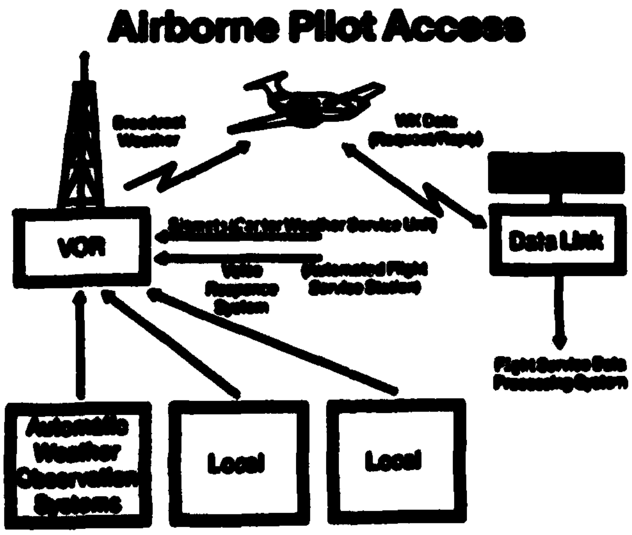

Figure 16

M I C R O W A V E   L A N D I N G   S Y S T E M

PROVIDES

- REDUCED SITE SENSITIVITY
- GREATER CAPACITY
- INCREASED GUIDANCE ACCURACY
- WIDE AREA COVERAGE

Figure 17

TRSB DESCRIPTION

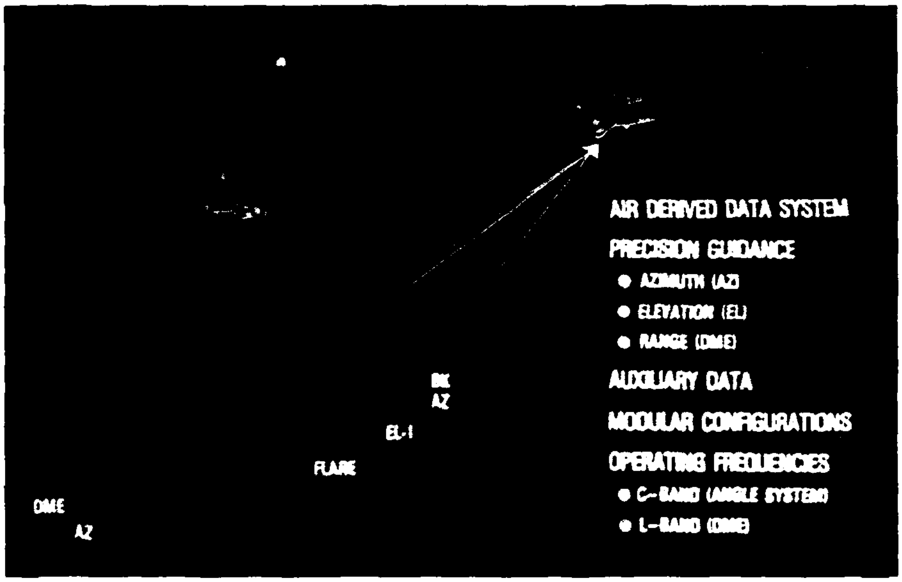

Figure 18

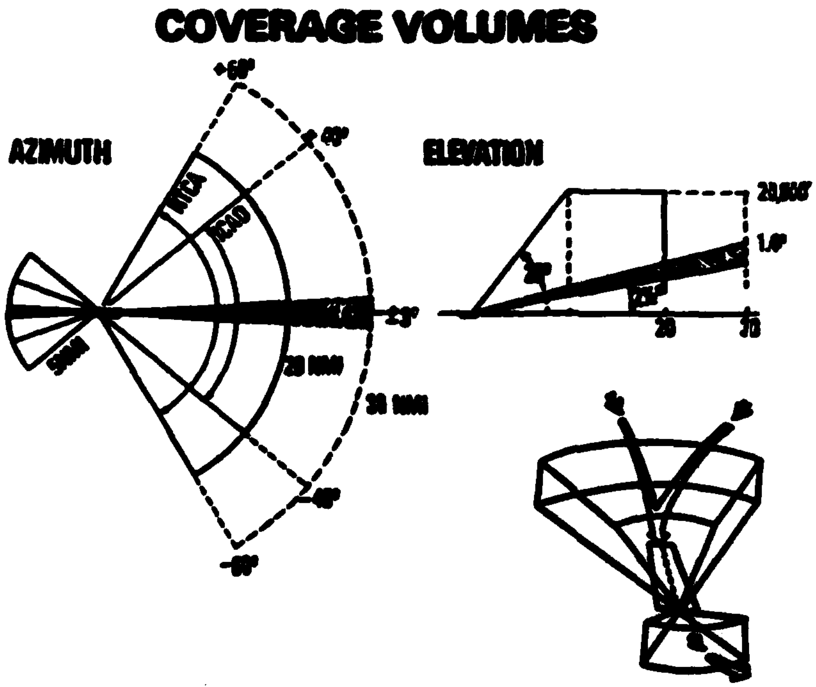

Figure 19

MODE S

PROVIDES

- IMPROVED SURVEILLANCE
  - •• ACCURACY
  - •• CONTINUITY
- GROUND-AIR-GROUND DATA LINK

Figure 20

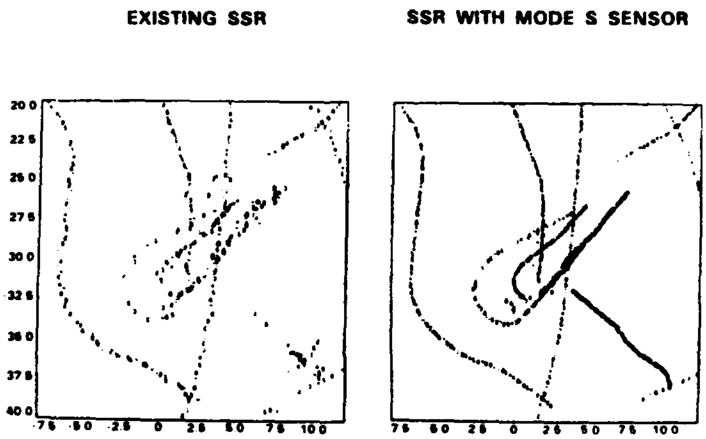

Figure 21

POTENTIAL DATA LINK SERVICES

WEATHER

ALPHANUMERIC

GRAPHICAL

TRAFFIC ADVISORIES

ETIS

CLEARANCES

Figure 22

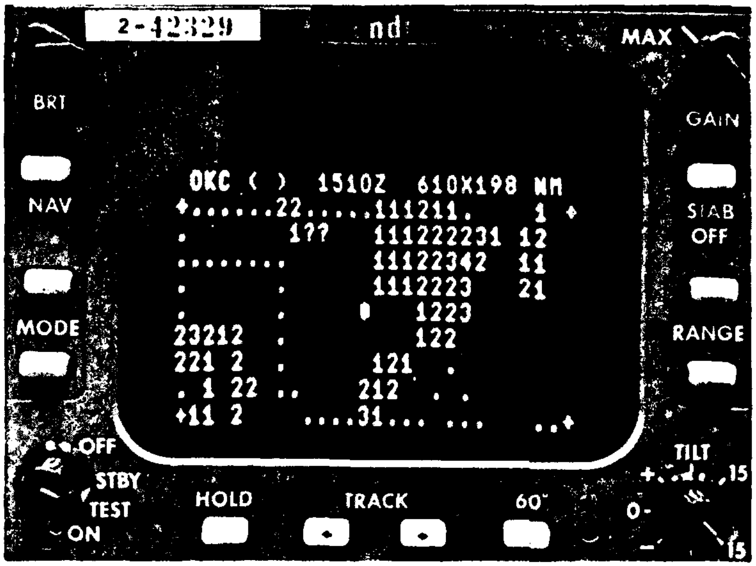

Figure 23

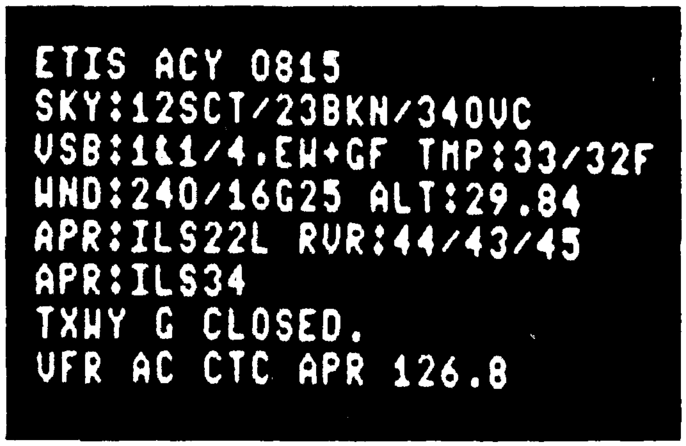

Figure 24

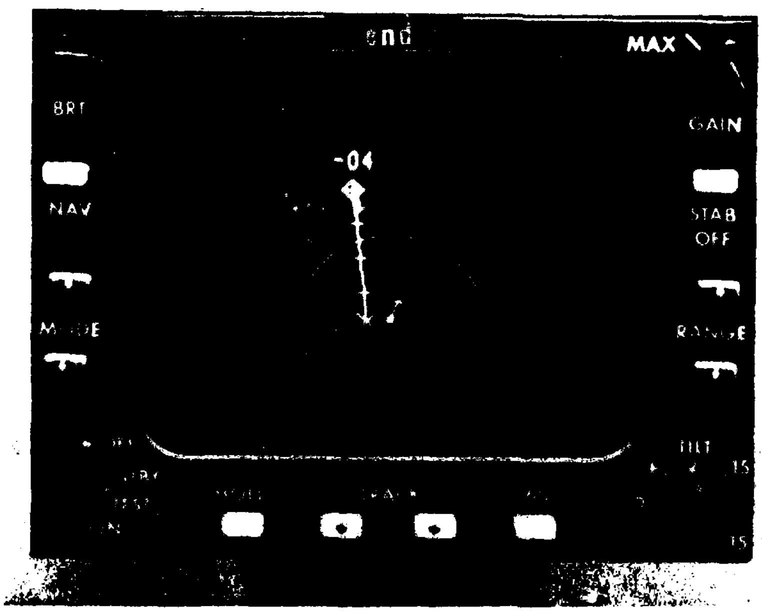

Figure 25

TCAS

GOALS

- FULL PROTECTION AGAINST TCAS-EQUIPPED AIRCRAFT
- USEFUL PROTECTION AGAINST SSR-EQUIPPED AIRCRAFT
- OPERATE IN HIGHEST PREDICTED DENSITY AIR TRAFFIC ENVIRONMENTS
- NOT INTERFERE WITH ATC SURVEILLANCE OR OPERATION

Figure 26

TCAS — SYSTEM DESCRIPTION

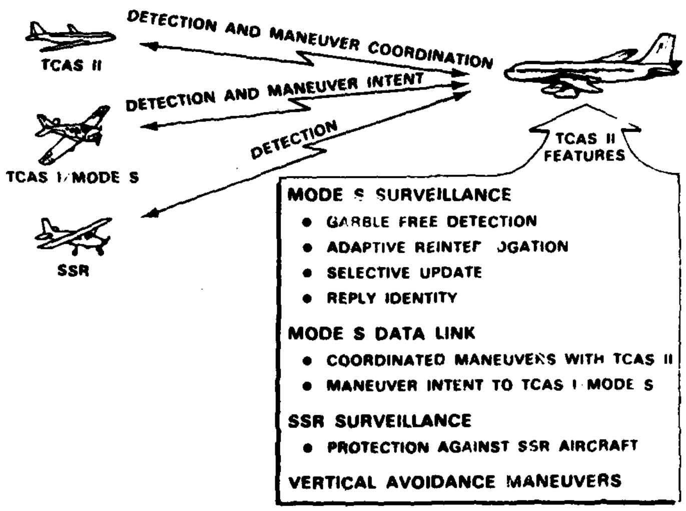

Figure 27

TCAS

VERSIONS

BASELINE TCAS (BCAS) — LIMITED CAPABILITY

- OMNIDIRECTIONAL INTERROGATION

TCAS II — FULL CAPABILITY

- DIRECTIONAL INTERROGATION
- RELATIVE BEARING INDICATION

TCAS I — LOW-COST GA VERSION

- RECEIVES MANEUVER INTENT FROM TCAS II
- PROXIMITY WARNING OF SSR-EQUIPPED AIRCRAFT

Figure 28

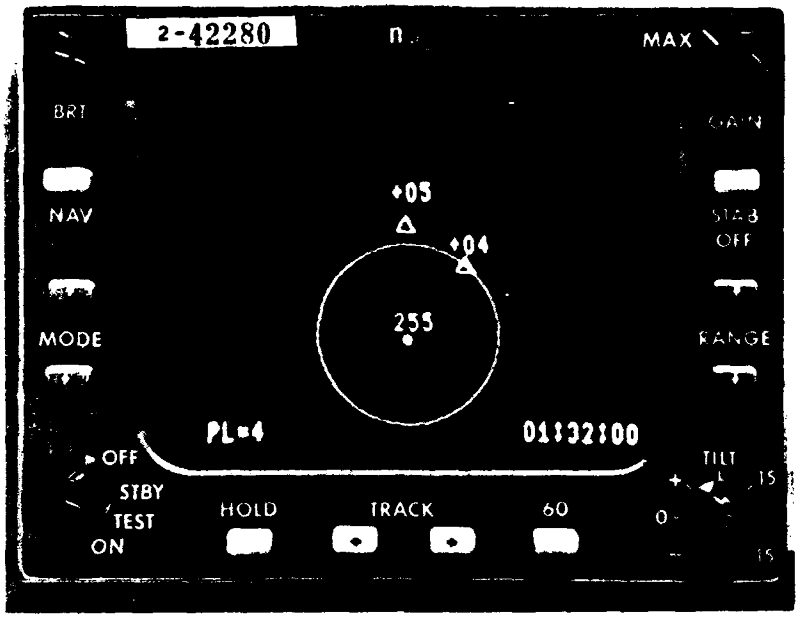

Figure 29

USER IMPLICATIONS

BENEFITS

- INCREASED SAFETY THROUGH COLLISION AVOIDANCE AND IMPROVED WEATHER INFORMATION
- REDUCED DELAYS
- REDUCED FUEL CONSUMPTION
- PROLIFERATION OF POINT-TO-POINT NAVIGATION
- NO ADDITIONAL EQUIPPAGE REQUIRED FOR MOST NEW SERVICES

SERVICES REQUIRING NEW EQUIPPAGE

- AIRBORNE COLLISION AVOIDANCE (TCAS)
- MODE S DATA LINK
- MICROWAVE LANDING SYSTEM (MLS)
- 25 kHz COMMUNICATIONS

Figure 30

• • •

MANAGEMENT & PLANNING CONCEPTS

BY

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SUMMARY

This paper outlines the processes used for management and control of air traffic. Some congestion in airspace or at airports is inevitable, the further ahead this congestion is foreseen. the more economically it can be resolved. A limit is set by the accuracy with which the future can be predicted.

Existing ATC systems necessarily use human controllers, who often significantly outnumber the aircraft under their control. It is not easy to see how this situation might be improved. Control tasks must be divided up between numerous controllers who, at busy times, cannot discuss each others problems in any detail. Controllers therefore solve only subsets of the total problem, and their solutions are significantly less efficient than theory indicates is possible. The extent to which "automation" might make possible cheaper or more efficient ATC is limited by safety considerations and difficult "human factors" problems.

INTRODUCTION

This paper will discuss the concepts which underlie air traffic management and control, and possible evolutionary changes in the ATC organisation. The emphasis will be on those aspects of ATC which have important economic implications, and since it is the airlines and their operations that are of greatest economic importance, the paper will concentrate on airline operation in controlled airspace. For those readers who are not familiar with ATC problems, the paper will begin with a simplified account of some of the fundamentals.

ATC is part of the air transport process, the object being to enable the aircraft to carry out their missions as safely and economically as possible. Efficient operation of a passenger jet requires it to cruise at a high level.

Table 1 shows, for a medium range passenger transport, powered by two RB211 engines, the distance that can be flown, for a given weight of fuel, at various flight levels. At any given level, the cruising speed is assumed to be chosen to give maximum range, and this speed is also given in the Table.

TABLE 1
Specific Range (at speed for max. range)
As a Function of Cruising Height

Height (Ft)	True Airspeed For Max. Range (KT)	Specific Range (NM/kg) x 10^3
0	290	56.0
5,000	305	62.3
10,000	318	68.7
15,000	345	75.0
20,000	370	81.3
25,000	388	87.7
30,000	420	94.0
35,000	440	99.9
40,000	Cruise Thrust Limit Exceeded	

It will be seen that flight at higher levels brings the further benefits that the flight is faster, and the aircraft and its crew are therefore sooner available for other work. There is a price to be paid for operation at these higher levels. A subsonic aircraft has an upper limit to the Mach number at which it can operate, and the upper speed limit falls with the speed of sound at increasing altitude. More seriously, the minimum speed at which the wings can develop enough lift to support the aircraft weight must rise as air density falls.

The demand for efficient operation in cruising flight thus pushes the aircraft into a region where the safe range of operationg airspeeds is fairly limited. This range is less, at the higher levels,than the range of windspeeds to be expected. It is therefore out of the question for an airline to achieve the punctuality expected in other forms of transport. ATC must expect, every day, to be faced with a different pattern of events, a pattern not predictable far in advance.

Table 1 suggested that the secret of economical operation was to cruise at the highest possible level. In reality, the economics of flight are more complex than this, because of the problems, and costs, involved in climb and descent. It is true to say, however, that all jet aircraft on roughly similar stage lengths are likely to be competing for the same optimum flight levels, and they will wish to spend as much of the flight as possible in cruise. There are obvious cost penalties if climb is restricted, or if the aircraft is descended prematurely on approaching the destination.

An airliner, cruising in clean configuration, requires a thrust from the powerplant that is about 1/20 of the weight of the aircraft. It is easily shown that to get the aircraft to climb 3 degrees would

require thrust to be cut to zero. In practice, the need for electrical power, cabin air etc. sets a lower limit, "flight idle", to the thrust.

Another limitation on descent rate stems from cabin pressurisation. The aircraft structure is normally designed to deal with an outside atmospheric pressure not greater than that in the cabin. Once an aircraft has descended to cabin pressure level, 8,000 ft say, a system of valves keeps the cabin pressure in step with the outside atmosphere, and the descent rate can no longer be sustained above about 400 ft/min without passenger discomfort. Descent from cruise level to ground, therefore, cannot easily take less than about 25 mins. ATC must therefore plan the descent about half an hour ahead, and during this time the aircraft will travel perhaps 150 miles, giving rise to possible co-ordination problems inside the ATC system.

ATC and ATM

The title of this paper covers 2 different concepts: "air traffic control" and "Air traffic management". ATC is here defined as the process which issues commands to individual aircraft, and using ATM to denote those processes which take decisions applying to classes of traffic, such as aircraft on a given route or departing from a given airfield.

All ATC and ATM processes require some measure of prediction of the future, and remedial action is called for if the predicted future seems unsatisfactory. Reference (1) suggested that the various processes could be classified according to the distance ahead in time to which they are looking.

We may begin with a time about 6 months before the flight, when the airline is putting together its time-table. Most large airports have what is often called a "scheduling committee" which looks at the forecast airport movement rates and compares them with the declared capacity of the airport. If the demand is too high, some process of negotiation is used to reduce peak demand to match the capacity. As well as these studies of airfield demand, usually carried out on a national basis, Eurocontrol uses a computer-based airspace model to detect situations where there is serious en-route congestion, and these problems are resolved in a similar manner. On the day when a flight is due to take place, things may have gone wrong. There may be failures in navigation aids or surveillance systems, or other factors, such as industrial action, causing a loss in traffic capacity.

The process known as flow-control involves some constraints on movement rate on one or more routes. In W Europe, at least, these constraints usually originate in one of the ATC centres. Constraints may take many different forms. They are sometimes imposed at relatively short notice but other restrictions remain in force for a long time.

Demand scheduling and flow-control fall within the earlier definition of air traffic management. ATC involves a shorter time-scale, and, indeed, ATC is little concerned with an aircraft until soon before taxi and takeoff. ATC's longer-term predictions are extracted from the flight-plan which an aircraft must file with ATC before flight in controlled airspace. This flight-plan includes the aircraft type and radio call sign, a full description of the route the aircraft wishes to fly, the desired cruising flight level, the airspeed in cruise and in climb, the planned departure time and so on. Most centres now have computers which extract from the flight-plan details relevant to the various control sectors, and display this data to the controllers a few minutes before the aircraft is due to reach them. Radar is used to give more accurate short-term predictions of aircraft position.

As already explained, aircraft cannot always be punctual. There is a need to revise flight-plan estimates of height and time at points along the route, in the light of ATC restrictions or earlier experience. In principle, this is easy when revising data stored in the local flight-plan computer. Ideally, data in computers in centres further along the route should also be updated. There are considerable practical problems when there are computer systems not always fully compatible with each other. There is work in Europe on the exchange of data between the computer systems of adjacent States, but much of the work is still experimental.

In areas, such as the N Atlantic, where there is no radar cover, ATC must rely on position reports from the aircraft. These are used to update data derived from the flight-plan and recorded on flight progress strips. Usually one strip is produced for each reporting point. In areas where there is radar cover, flight progress strips are still produced, but the aircraft are not usually required to report height or position, since this data can be derived from secondary radar.

When an aircraft enters an ATC centre's area of jurisdiction, a controller will issue a "procedural clearance", based on the flight-plan but with any necessary constraints on height or speed. This clearance is designed to provide a safe, if not necessarily expeditious, trajectory for the aircraft and commonly covers at least 15 minutes of the flight. In the event of radar or communications failure, this plan must be adhered to, but under more normal circumstances the radar controller may be able to lift the restriction at some later time.

The radar controller relies mainly on data on his electronic displays. Aircraft can be identified by means of a secondary radar identity code, assigned by ATC, and modern radars label their plots with identity and height derived from SSR. In general,surveillance radar gives a measure of the relative position of a pair of aircraft that is more up-to-date and more accurate than information derived from pilots reports of their positions. It is also possible, from immediate past history, to derive a reasonable estimate of ground speed and track that is not usually available by any other means. It can also supply some of this data for aircraft that are not co-operating with ATC. The separation standards used by radar controllers allow a much closer spacing than does procedural ATC, and controllers using radar are often working on a shorter time-scale.

COLLISION AVOIDANCE

Airborne collision avoidance, it can be argued, is not part of ATC but some kind of substitute for it.

It deserves mention, however, because the presence or absence of an effective version of such a device must have a considerable influence on ATC concepts. The simplest collision-avoidance device is the pilot's eyeball "See-and-avoid" is the basis of flight safety in much of the World's airspace. The weaknesses of the system are its failure in bad visibility, the limitations on the directions in which a pilot can observe approaching threats, the difficulty of seeing a threat at an adequate range, even in clear sky, and, not least, the difficulty of choosing an appropriate escape manoeuvre.

Pressure for the adoption of some electronic airborne collision-avoidance device has mostly come from the USA, the main objective being to reduce the risk of collision between air carriers and general aviation traffic.

The most recent of a succession of devices designed to meet this need is the Traffic Alert and Collision Avoidance System. (2). This is based on SSR Mode S, although it offers limited protection against aircraft carrying earlier versions of SSR.

TCAS, like earlier systems, has no knowledge of the intentions of any possible threat, and the TCAS logic should therefore, ideally, be based on worst-case assumptions about any other aircrafts' future intentions. Although the theory underlying TCAS does not appear to have been published, the logic would seem to be best adapted to aircraft in straight-line flight at constant speed.

TCAS must be compatible with the operation of present-day ATC as practised in domestic US airspace. It is perfectly in order for an aircraft to be in flight along and airway, under instrument flight rules, whilst another aircraft is in flight immediately above or below the first, under visual flight rules and separated by 500 ft. In this situation, if both aircraft carried TCAS, they would receive "do not descend" or "do not climb" advisory messages. If one aircraft did not have TCAS, or if the advice was, for some reason, ignored, a positive evasive manoeuvre would be commanded only after some further loss of height separation. For an aircraft in straight-line flight, TCAS parameters should give rise to an alarm only 20 - 30 seconds before impact. When aircraft are not both in straight-line flight, the warning time may be even less. Consider, for example, a pair of aircraft, one in straight-line flight and the other flying a rate one turn, as in holding pattern. Suppose that the holding aircraft begins to descend at 1000 ft./min. and that the two aircraft are due to collide. It can be shown that only about 15 seconds before impact will TCAS deliver its first warning. It seems, therefore, that the aircrew need to obey TCAS commands without pausing to consider the wisdom of the manoeuvre.

The situation described above was chosen to be unfavourable to TCAS. If it were used merely as a backup to the ATC system, and achieved only a 30% success rate in catching blunders, TCAS would still be a valuable device. It does not, however, appear likely to be able to take over many of the tasks presently carried out by ground-based ATC. Nevertheless, TCAS could play a useful role in ATC, not merely in the USA but in many parts of the World, provided that two conditions are satisfied. Firstly, the range of sensitivity settings, presently specified in the US National Standard, (3) needs to be broadened. Secondly, it is important that the strengths and weaknesses of TCAS should be more clearly understood.

COSTS AND AIR TRAFFIC CONTROL

The present collection of papers is really concerned with ATC economics. It goes without saying that ATC has to achieve an acceptable level of safety, the problem is to achieve that safety at minimum cost. There are really two kinds of cost, the cost of operating the flights and the cost of the ATC organisations. Attempts are usually made, one way or another, to pass the cost of ATC on to the airspace user, so for present purposes it will be assumed that the object is to minimise the overall cost, including the cost of ATC.

Consider first the direct cost of operating the flight. Even if airspace had unlimited capacity, there would still be traffic limitations set by the airports. Given an irregular pattern of demand for the runways, some congestion is inevitable, even at traffic levels far below the ultimate capacity of the airport. The earlier this congestion is foreseen, the more opportunity there is for the airline or aircrew to re-arrange their activities so as to minimise the resulting economic penalty. The following paper will discuss techniques for increasing the accuracy with which one can predict the time of arrival of an aircraft at its destination, half-an-hour ahead, say, and the cost savings that might result. Some form of en-route speed reduction is undoubtably a cheaper way of achieving a given delay, than is flight in low-level holding pattern with the aircraft in a high-lift high-drag configuration. Cheaper still is a delay before engine start-up.

The difficulty, of course, is that forecasts of future delays are fallible. If delays are imposed in anticipation of congestion later in flight, some of these delays will later be found to have been unnecessary. This point is illustrated by a simple computer simulation described in ref. (4) which was concerned with the flow of traffic inbound to a "gate" in the vicinity of a destination airport. Similar effects no doubt arise elsewhere in ATC, although the flow-control process, for example, is less easy to analyse. Existing air traffic control systems are generally based on the assumption that traffic is not particularly predictable. It is necessary, therefore, to operate an ad hoc basis, to accept aircraft whenever they chance to arrive, and to attempt to impose a precise pattern on the traffic only as it approaches the landing runway. There have been proposals (5,6) for systems in which constraints are applied to improve aircraft predictability and to organise the traffic pattern more tightly. Study (7) suggests that the economic penalties are too great to justify the adoption of these techniques.

ATC ORGANISATION

So far, this paper has been concerned with the various tasks to be performed by an organisation referred to as ATC. This organisation comprises a highly organised team of people, and we must now discuss the way in which the control tasks are shared between team members.

Controlled airspace is normally divided up into "sectors". An "en-route" sector is usually responsible for the airways and associated upper air routes lying within specified geographical boundaries, as well

as for traffic crossing these routes. "Terminal" sectors are responsible for traffic arriving at, or departing from, airports within the sector. Sectors are sometimes bounded in the vertical as well as in the horizontal plane. A terminal sector may, for example, be concerned with traffic below 15,000 ft, whilst an en-route sector is responsible for the overflying traffic.

As seen by the pilot, a "sector" corresponds to a single RT channel. The service which ATC provides to aircraft on this channel may, in fact, come from a small team of controllers headed by a "sector chief" who is concerned with co-ordination with adjacent sectors as well as with overall supervision of events in his own sector. In the London centre, for example, a typical en-route sector has four sector radar controllers and perhaps two assistants. The sector team may also include a military controller who handles, on a different communication network, military operational aircraft who may wish to cross the civil routes. Division of tasks between radar controllers in a given sector is also often on a geographical basis.

Although the controller's equipment is usually standardised, the repertory of fixed telephone connections and of RT channels to which the controllers in a given sector have access, is often tailored to the specific requirements of their sector. A controller who takes up work in a sector other than one with which he is familar needs some little time to adapt to the different facilities and to local problems.

There are several limitations on the size of a control sector. There must, for example, be time for all the RT traffic to share a single speech channel without risk of serious delay to urgent messages. There are also limits to the length of an airway that can be mapped on a single radar display without a risk of the picture becoming too confused when aircraft approach each other in plan position. Finally, and most important, is the not-too-well-defined, but certainly finite, limit to the number of aircraft which a controller can safely handle at one time.

The number of sectors needed to control traffic within the jurisdiction of a given control centre is therefore determined by the upper limit on the traffic which a given sector can handle at peak time. Since it must be possible for controllers to take breaks for meals etc., and since several teams of controllers are needed to provide an ATC service for 24 hours of each day, it can easily happen that for every controller whose services may be necessary at traffic peak, about ten controllers have to be employed. For example, it has been stated (8) that the centre handling en-route traffic in Northern France needs about 480 controllers in addition to 100 controllers for each of the terminal facilities at Orly and Roissy.

Traffic into, out of, and overflying the Northern France control centre is about 700,000 movements per year, an average of about 2000 aircraft per day, or 2.9 aircraft per controller per day. This result is probably typical of ATC as a whole, and in this system a given controller may be working very hard indeed.

The explanation for the above rather startling result is obvious enough. Traffic is not uniformly divided between the hours of the day or the days of the year, nor does traffic peak simultaneously in all sectors. The organisation is such that a controller in a quiet sector can usually be of little help to a hard-pressed colleague in another, and there is no way in which extra staff can rapidly be re-introduced into the control system to take over part of the task.

At times of light traffic loading, it is sometimes possible to combine two adjacent sectors so that one team can handle them both. This is known as "bandboxing" and is used to free controllers for training and other activities, but even this limited reduction in the necessary scale of effort is not without its problems.

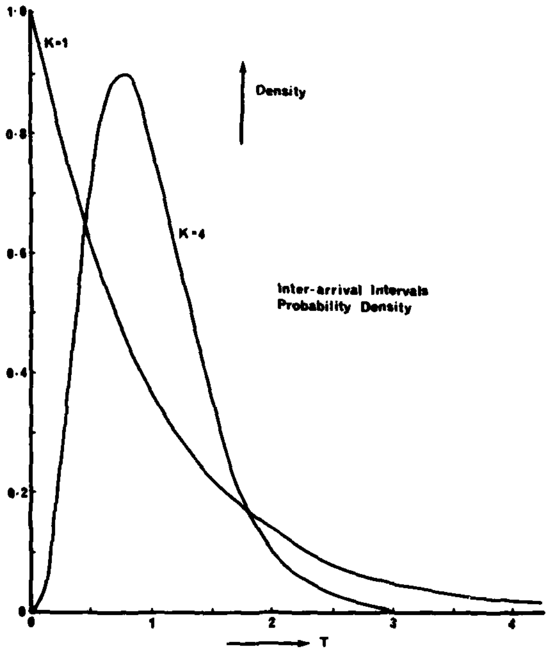
The need to divide up the control tasks between a large number of controllers brings other difficulties to ATC. Most controllers must keep a continuous listening watch on the RT, since an urgent problem may arise at any time. If two controllers, listening to different RT channels, wish to discuss some mutual problem, interruptions from the RT may make this very difficult. If each RT channel is occupied half the time say, then there is only a 25% probability that, at a given instant, both controllers will be free to speak or listen. For a long conversation, the chances are much less, and controllers often have to use their assistants to negotiate on their behalf.

Consider, however, 10 controllers who may be concerned with activities at a single airport, handling 50 movements per hour. A committee of ten members cannot meet to take a decision every 70 seconds. The problem has to be solved by subdividing the control task and assigning certain regions of airspace, flight levels or runways to the exclusive use of some subset of the total traffic. This division has the effect of aggravating the consequences of the inevitable irregularity in the demand on the various available facilities. If, at a time when a particular class of traffic was making a heavy demand on a given route, say, it would be better if some of the traffic could make use of the airspace normally allocated to some other class of user.

Consider a stream of aircraft wishing to use a given facility, each arriving at a random instant in time. Suppose that each aircraft then ties up the facility for a fixed length of time; slightly less than the mean interval between arrivals, here taken to be unity. The curve marked "k=1" in Fig. 1 then shows the relative probability that the time gap between two successive arrivals falls within a given small interval centred about the value of T plotted on the horizontal scale. Ideally, we would like the aircraft to arrive at equally spaced intervals, so that the distribution would consist of a single vertical spike at T=1. Since our aircraft have each been assumed to tie up the facility for a time less than unity, all aircraft could then be handled without delay.

As the K=1 curve shows, many pairs of customers are, in practice, closely spaced, which means that they must queue, whilst other pairs are widely spaced, which may result in an idle period.

If we had four such streams of customers, each requiring similar facilities and arriving at the same average rate, each stream and its facilities being segregated from the others, then this result would



apply to each stream. If, however, the four streams could be regarded as a single flow of traffic, and the four facilities were used in sequence then the distribution of time intervals between traffic reaching any one facility would be shown by the curve marked "k=4". This is still not our ideal vertical spike, but it is a much better approximation to it. The mean delay, given this "k=4" organisation, would be about a quarter of that experienced with the segregated operation corresponding to k=1.

To repeat, the practical problems are formidable. Neither the controllers nor the pilots would be able to forecast far in advance exactly what was going happen, at least, not without a lot of assistance from computer driven displays, automatic data links and so on.

Fig. 1

ALTERNATIVES TO ATC?

In the present state of the World's economy, it is being argued, particularly in the USA, that more of the responsibility for traffic management should be given to the aircrew, with a subsequent rundown of the ground organisation (9). It is sometimes argued that TCAS could play a major part in this new system. The present writer feels that TCAS may make possible an appreciable reduction in mid-air collisions between uncontrolled aircraft, but that it will not make possible any major reduction in the size of the ground-based ATC organisation unless the traffic presently flying under air traffic control is prepared to face a fall in safety standards.

A more plausible argument supports a system based on an electronic cockpit display which shows the aircrew the position of any nearby traffic, together with a traffic plan devised on the ground by ATC. The aircraft has the responsibility for implementing its part in this plan, whilst maintaining a safe separation from other traffic. It may be argued that this scheme reduces the demand for ATC effort by putting an extra crewman on the flightdeck, but at least it avoids the need for controllers to sit watching empty sky. It seems clear, however, that the changeover to such a system would necessarily be a laborious process. Although it might prove, overall, to be a cheaper way of handling air carrier traffic, it must be remembered that there are other airspace users, hitherto neglected in the present paper. Many private fliers might find the necessary avionics more expensive than their airframe, and pilots of high-performance military aircraft might well be too busy to undertake the necessary surveillance.

Even if we transfer to the flight deck some of the work of separating an aircraft from its immediate neighbours, there is still a need, in areas of high traffic density, for this longer term planning. It is necessary to determine the order in which aircraft are to use the runway, to share out the available routes, flight levels, and so on. These tasks have to be carried out by some central, ground-based, organisation. Regardless of any avionic developments, we still have the ATC system with its weaknesses. The system is still likely to be man-power intensive, because of the difficulty of matching the number of controllers on duty to the traffic problems existing at a given instant. There also remains the problem of co-ordinating the planning activity of a large team of controllers to obtain an efficient overall solution. Earlier reference was made to the difficulty experienced by controllers who wish to discuss a problem with a colleague in the same control centre. If we are discussing long-term plans, in particular, there is a need for co-ordination between adjacent control centres, often across national boundaries. Copenhagen, for example, has airspace contiguous with that controlled by eight other centres. Only 11 miles up the approach path to Kastrup from the East is the boundary of Danish and NATO airspace.

The solution that is often put forward to both these problems is "automation". It is argued that computers can take over many of the tasks, presently carried out by humans, with a saving in man-power. At the same time, one can imagine a computer which holds in its database a picture of a large volume of airspace and which can freely exchange data with its neighbours. Such a machine should have the potential to devise more comprehensive, and presumably, therefore, more efficient solutions to traffic congestion problems. A lot of experimental work, using simulated air traffic, seems to support these arguments.

The real difficulty with "automation" in ATC is the high standard of safety that is demanded. It is necessary to have a system that can solve problems that may be arising for the first time. With careful engineering, one might be able to devise an automatic system which can solve a number of standard problems. The difficulty is to provide a safe mechanism that can recognise a non-standard problem that cannot safely be left for the software.

The only mechanism available for this task is the human controller. He must have an interesting and rewarding task in the ATC organisation, one that ensures that he is alert and familiar with the traffic

situation. He must also have a clear understanding of the behaviour of his automated system, and a means of over-riding machine decisions when these are based on an inadequate picture of the situation. The "human factor" problems are formidable.

It should be noted, however, that the level of reliability required will decrease as the time-horizon increases. An error in the earlier planning stages should leave time to find an alternative solution that is safe if not very efficient. Clearly, we can run a bigger risk of a moderate financial penalty than we could tolerate when there is a serious risk to human lives.

To sum up, the management and control of air traffic is a subtle and complex task which relies at present almost entirely on the skills of the individuals who are directly involved in the movement of the traffic. This system has its drawbacks and it seems likely that, with the growth of computer technology, "automation" will take over some, at least, of the tasks presently performed by human controllers. This process of "automation" will probably continue to be implemented with considerable caution. Man has an ability to invent solutions to unexpected problems that the latest, largest and fastest computers cannot begin to emulate.

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DYNAMIC CONTROL OF INBOUND FLIGHTS

FOR

MINIMUM COST OPERATION

by

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SUMMARY

The Zone of Convergence (ZOC) concept is proposed as an essential short-term Air Traffic Control contribution to the economics of Air Transport. It is established that, when considering traffic inbound to a medium to high-density terminal, this approach could reduce fuel consumption by some ten to thirty percent, this value being referred to the total fuel burn in an extended area including and surrounding a main terminal and extending over some 100, ideally 300, nautical miles. The selection of profiles tailored to the operators' criteria, whether constrained by Air Traffic Control or not, is discussed in some detail. The compatibility of the techniques proposed with on-line operation is found to be satisfactory. This conclusion results from tests conducted using ATC simulation facilities, airlines' flight simulators and on-line exercises involving regular scheduled flights.

1. INTRODUCTION

1.1 Present status

Today, when inbound aircraft are handed over to approach control they are already relatively close to the assembly points, that is to say, at some twenty to forty nautical miles from the runway. Scheduling, possibly sequencing, whenever computer-assisted or conducted manually, is then started in a manner practically independent of the upstream conditions. Of course, such a procedure nevertheless allows use to be made of the maximum runway capacity available, but in high-density air traffic terminals this scheduling can only be achieved at high cost through path stretching and/or holding at relatively low altitude.

1.2 Proposed ATC approach

Techniques compatible with real time and on-line operations are currently available to provide Air Traffic Control with accurate estimates of time, consumption and cost of transit for any aircraft requested to follow a particular control pattern between two given positions. Based on such techniques, a global approach is proposed, integrating en-route, approach and landing phases of inbound flights. At all times, expedition of traffic is ensured in the most economic manner, safety being considered as a prime constraint. To this effect, adequate use is made of the available on-board equipment, operational capabilities of the aircraft and the potential of tools available for conducting on-line the prediction, control and economy assessment of flight profiles.

The traffic is controlled over a large area including and surrounding at least a main terminal and extending over some 100 to 300 nautical miles. The relevant area is referred to as a Zone of Convergence (ZOC). No assumption is required regarding the incoming traffic, except that it is, as usual, free of conflicts when arriving in the zone, that is to say when the transfer of control occurs.

Two illustrative configurations of a Zone of Convergence will be presented in the course of this paper. For ease of reference, the zone used for exposing the concept to real time operation in an actual ATC environment is shown schematically in Figure 1 (Refs. 1 and 2). The area covers the whole of Belgium and includes Brussels-National Airport, representative of a European medium-density traffic terminal.

1.3 Inherent potential

The developments undertaken within the Zone of Convergence concept provide an adequate framework to realise the following particular inherent objectives :

(a) Appreciable increase in safety;
(b) Reduction of controller workload;
(c) Maximum use of available ATC capacity, particularly at the runway;
(d) Minimum flight operating cost for the overall traffic in the zone, and as a consequence
(e) Consumption of fuel in line with operators' requirements;
(f) No individual penalty resulting from the use of a particular type of aircraft.

The investigations conducted to date and summarised in this presentation indicate, in particular, that such objectives could be achieved through the use of trajectory control, possibly complemented by some sequencing limited to alterations of one, or occasionally two, positions in the "First Come, First Served at the Runway" landing sequence.

1.4 General contents

In this paper, the following aspects will be covered, each section reflecting part of the activities conducted and results obtained to date.

The selection of aircraft trajectories to meet a particular criterion when free to operate or constrained by Air Traffic Control will be discussed in Section 2. The essential criteria considered aim at minimising the consumption or the direct operating costs of flights as seen by the operators, which results in use of the maximum runway capacity available.

Section 3 presents and analyses techniques suitable for the control of the time of arrival at the runway and the absorption of delays at or preferably before the assembly points. These are compared particularly in terms of ATC penalties imposed as a result of the traffic situation at the arrival airport.

Several estimates have been given by various national (Ref. 1) and international Administrations (Refs. 2 and 3) for the excess fuel consumption resulting from the use of non-optimal trajectories between two airports. What is the significance of the Zone of Convergence concept in terms of potential benefits as expressed in quantities of aviation fuel or operating costs ? Section 4 indicates how nugatory consumption can actually be measured in extended terminal areas.

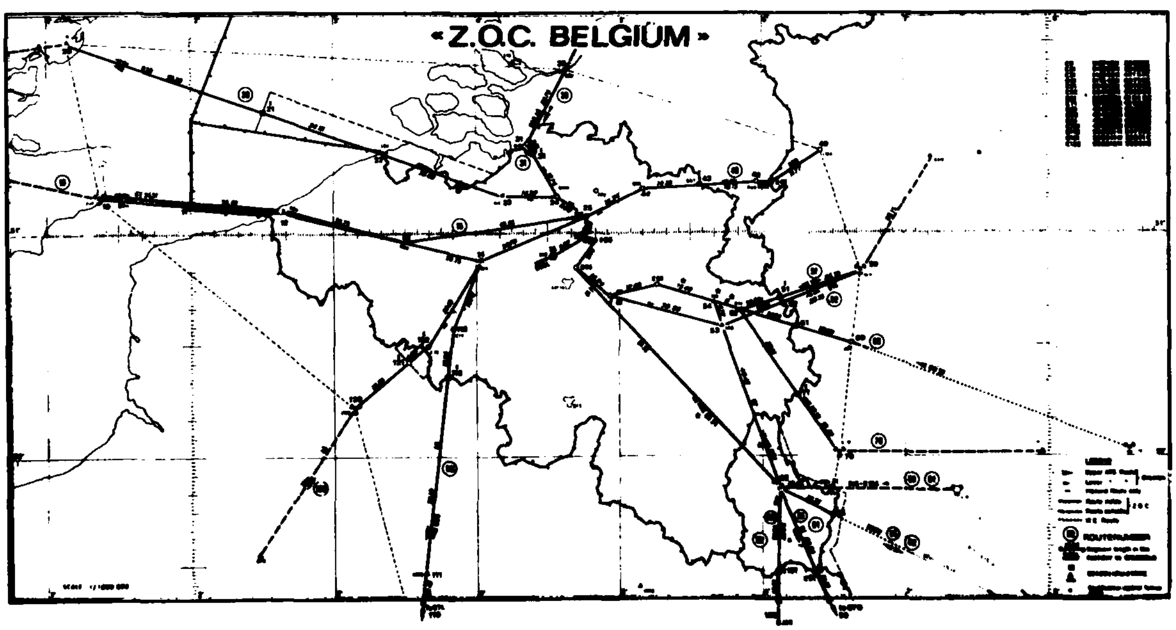
The analysis of the situation observed in present medium- to high-density traffic terminals, then, suggests a restructuring of the control and airspace in line with the Zone of Convergence concept as described in Section 5.

Section 6 outlines some of the specific ground-air coordination aspects. It shows, in particular, how the essential liaison between the ground-based control and the onboard control components can be defined to transfer, acknowledge and confirm the computer-generated directives needed to ensure the control of the trajectory of the aircraft in terms of the time window available at the landing end.

At this time, only limited real time and on-line experiments have been run. Their essential purpose was to test the compatibility of the prediction and control methods developed with on-line operation. The experimentation included, besides simulation exercises, actual control of regular scheduled flights operated to or from Brussels, the other end being London, Birmingham or Zurich. A summary of the relevant results is presented at the end of Section 6.

The essential conclusions and recommendations are listed in Section 7. They cover the results of the investigations and experiments conducted to date, as well as recommendations pertaining to the continuation of the programme of development required before they can actually be implemented in operational centers.

The list of references presented in Section 8 is far from being exhaustive. It essentially relates to work conducted in this particular field by the General Directorate of the EUROCONTROL Agency in association with institutions of the Member States of the European Organisation for the Safety of Air Navigation. Additional bibliography is included in the reports and articles cited.



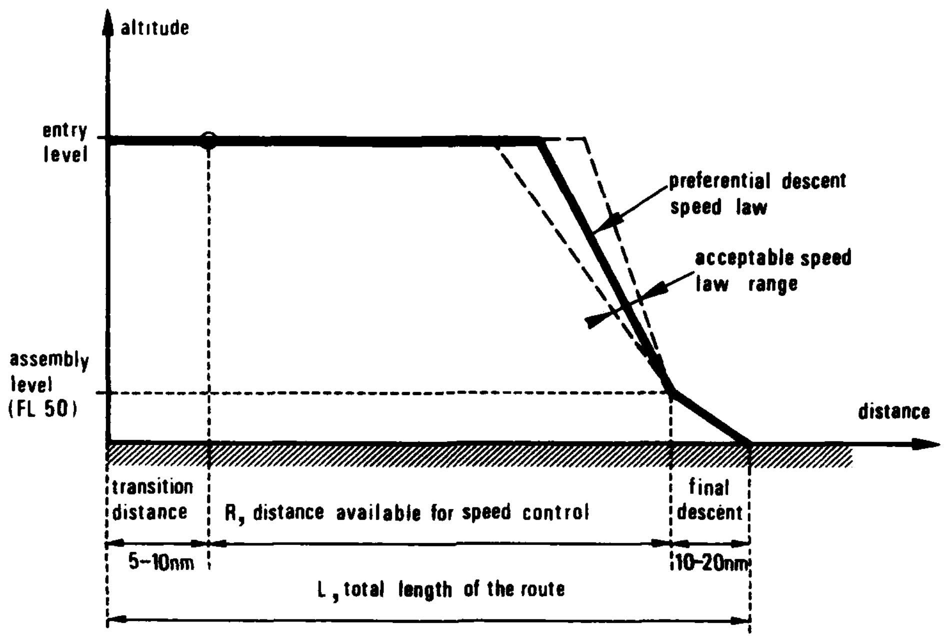
Configuration used in a real-time ATC simulation

Figure 1

2. ANALYSIS OF INTEGRATED CRUISE/DESCENT PHASES

2.1 Trajectory and consumption data

In the zone of convergence concept a flight is normally composed of the cruise or part of it, and descent phases. If a change of cruise level is necessary, it will generally correspond to a descent. Accordingly, it appears helpful to introduce in a convenient manner cruise and descent data suitable for determining the time and the consumption required for the transit into the zone along a segment configuration such as suggested in Figure 2. The method chosen (PARZOC) makes use of aircraft trajectory and consumption information presented in a parabolic form. It appears quite suitable for use in the zone of convergence context (Refs. 7 and 8). Furthermore, the experiments conducted to date and subsequently discussed briefly have shown the compatibility with real time and on-line operation (Refs. 9 and 10).



Schematic inbound flight configuration

Figure 2

The analysis which follows is made by using the aircraft performance data presented in the PARZOC form as given in Reference 7 for five typical families of aircraft (Table 1). A more detailed form and an extended contents is presented in Reference 8 for eleven types of aircraft ranging from a light-weight short-haul aircraft similar to the Fokker F-27, to wide-bodied long-range aircraft such as the McDonnell Douglas DC-10 and Boeing B-747.

2.2 Transit fuel versus time relationship

In the zone of convergence concept, the transit speed profile is characterised by two components, one for the cruise (subscript "cr") and one for the descent (subscript "de"). Between the entry point and the assembly point, the time of transit and the amount of fuel consumed depend on the pair of speed profiles selected. The relationship between consumption and time for a given flight is illustrated in Figure 3(a) for a aircraft of the McDonnell Douglas DC-10 family (Aircraft 3A) : this diagram is based on data published previouslsy (Ref. 7).

2.3 Time of arrival control range and its impact on fuel consumption

Obviously, the possible spread or possible control of the transit time depends on the range of cruise and descent speeds that are acceptable from the operational viewpoint. In Figure 3(a) the extreme range is used, namely from 220 kt to 340 kt CAS for both cruise and descent. For a cruise phase at FL 300, these values correspond to Mach number values equal to 0.59 and 0.88 respectively. This range makes it possible to illustrate the effect of speed limitations. Indeed, if for any reason the acceptable speed range is reduced, the range of control available for the transit time is reduced accordingly. Figure 3(a) contains sufficient information to show how this control range varies with the speed interval considered.

The minimum and maximum transit times correspond to the combinations of minimum and maximum speeds. These points are designated e1 and e2 respectively. If the minimum transit fuel, designated mf, is used as a reference, the range of control for the transit time is made up of the two intervals located to the left (acceleration) and to the right (deceleration) of the minimum fuel transit point (mf). The variations in fuel consumption by reference to mf usually reach their maximum values at one of the speed interval

boundaries, most often when both cruise and descent speeds are at their extreme values. For the domains considered in Figure 3(b), the values obtained are summarised in Table 2. This table illustrates the range within which the time of arrival can be controlled, for three speed ranges, together with the associated variations in consumption.

AIRCRAFT	DESCRIPTION	REPRESENTATIVE
1A	Short-haul Twin-turbofan 24 tons l.w.	F-28
2A	Short-haul Twin-turbofan 40 tons l.w.	B-737
2B	Short/medium-haul Tri-turbofan 55 tons l.w.	HS-Tri 3
3A	Wide-body Long range Tri-turbofan 160 tons l.w.	DC-10
3B	Wide-body Long range Quadri-turbofan 240 tons l.w.	B-747

Illustrative selected sample of aircraft

Table 1

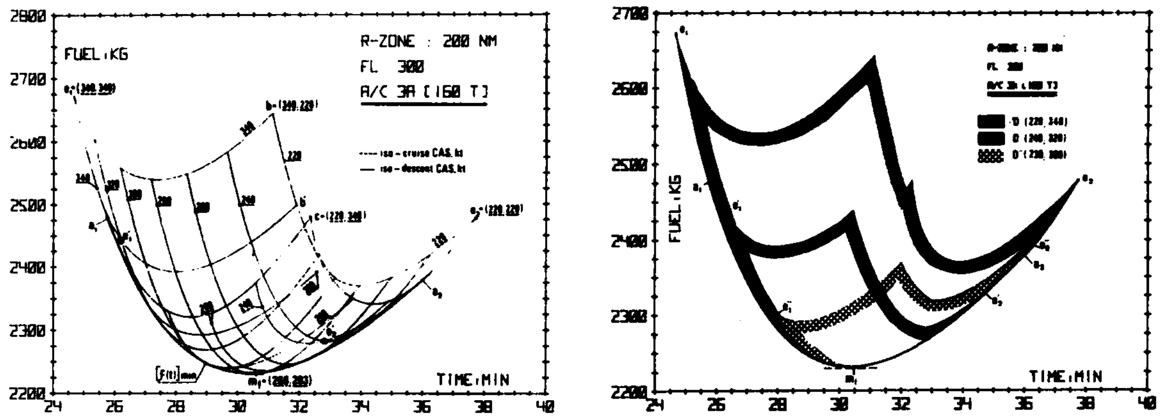
If a particular speed range is considered, for instance limited to 20 kt around the minimum fuel point for both cruise and descent, the control range and consumption variations are those given in the same table in Domain 4. In this particular example, the control of the direct-transit time extends from two minutes before the minimum fuel time (possible acceleration) to two and a half minutes after that time (possible deceleration); the resulting fuel penalties are roughly the same at both ends, namely some 36 kg.

In general, the minimum fuel required to transit from entry at cruise level to 5,000 ft and the fuel associated with the operational fastest transit define the practical range of consumption for direct flight. This is illustrated in Figure 4(a) and (b) for aircraft representatives of the Boeing B-737 (2A) and B-747 (3B) families respectively.

2.4 Minimum fuel under time constraint

If the aim is to consume a minimum quantity of fuel, the profile to be used should correspond to point mf. The cruise and descent speeds defining point mf constitute the absolute "preferential profile", independent of the extent of the cruise/descent flight segment. Accordingly this fixes the preferential transit time and, consequently, the arrival time at the assembly point.

In view of the other traffic also present in the system, Air Traffic Control may advise arrival at the assembly point at a time other than tmf. If the corresponding transit time is within the operational interval (e1, e2), speed profile control will be sufficient to ensure that the aircraft arrives at the requested time. In general, there will be an infinite number of cruise-descent CAS combinations to meet that time-constraint but only one combination will correspond to a minimum consumption. This profile is obtained at the intersection of the envelope designated $[\bar{f}(t)]$min on the diagrams, see for instance Figures 3(a) and 5(a), with the particular value of the transit time required.



(a) (b)

Fuel versus time relationsip for given ranges of cruise and descent speed profiles

Figure 3

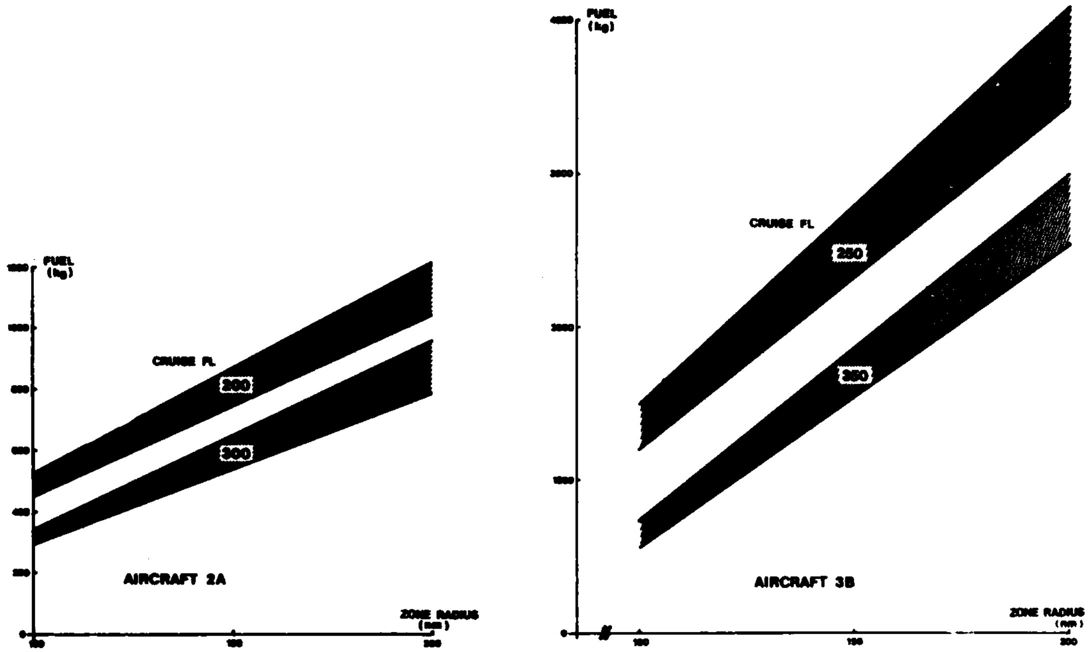
Zone extent nm	Lower limit a_1				Upper limit a_2				Range
	Time (min)	Fuel (kg)	ΔFuel (kg)	ΔFuel (%)	Time (min)	Fuel (kg)	ΔFuel (kg)	ΔFuel (%)	$ta_2 - ta_1$ (min)
100	14.1	416	11	2.5	19.9	369	4	1.2	5.9
150	21.0	715	14	1.9	28.2	642	6	0.9	7.2
200	27.9	10.4	16	1.5	36.4	915	6	0.6	8.6
250	34.7	1312	16	1.2	44.6	1188	6	0.5	9.9
300	41.6	1611	17	1.1	52.9	1462	5	0.4	11.3
350	48.5	1909	18	0.9	61.1	1735	5	0.3	12.7
400	55.4	2208	18	0.8	69.4	2008	5	0.3	14.0

Effect of zone extent on the control of time of transit
(light-weight short-haul aircraft, cruise altitude 25,000 ft)

Table 2

Accordingly, where economy or fuel consumption is the transit criterion, it is clear that the only cruise-descent profiles to be considered are those associated with the envelope in the fuel-time diagram. For clarity, we have reproduced from Figure 3(a) to Figure 5(a) the fuel versus time relationship for a set of particular profiles. These include minimum and maximum cruise and descent speeds, the minimum minimorum fuel transit, and the minimum fuel transit when the transit time is imposed by the ATC authority.

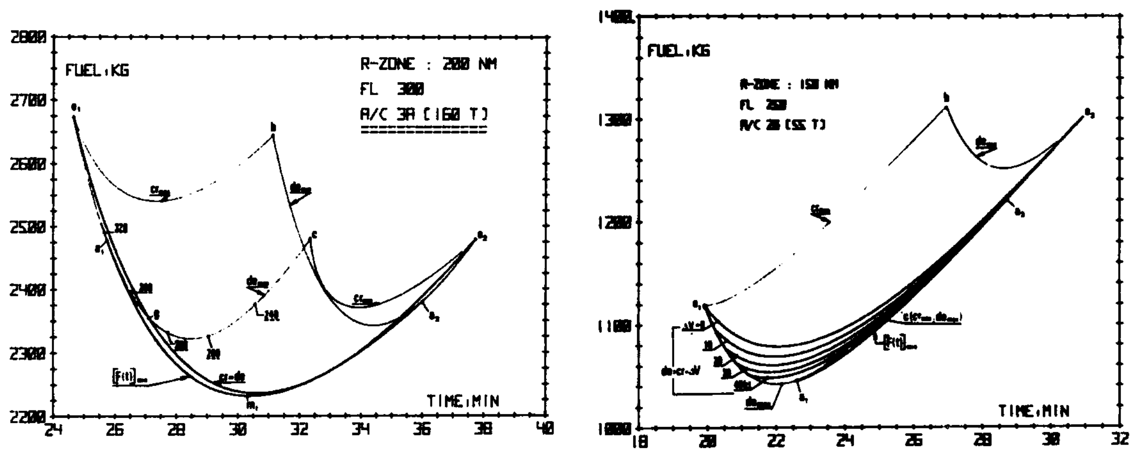
Obviously, the envelope determines the minimum fuel procedure but in the operationally acceptable speed range only. In the diagram, this range falls between points a1 and a2 where one of the speed components reaches the corresponding maximum value (or possibly minimum value). In Figure 5(a) for instance, at a1, the descent speed reaches the maximum acceptable value, while at a2 the descent speed is at its minimum. This implies that in the case illustrated in Figures 3(a) and 5(a) for transit times associated with e1 and a1 and a2 and e2, the minimum transit fuel procedure will impose maximum and minimum descent speed respectively. The cruise CAS results from the intersection of the relevant extreme descent-CAS with the value of the requested transit time.



(a) (b)

Range of fuel consumption for direct transit

Figure 4



(a) (b)

Fuel versus time relationship for particular speed profiles

Figure 5

2.5. Smooth cruise-to-descent speed transition

In the various investigations conducted at the beginning of the ZOC project, it emerged that a particular family of speed profiles for which both cruise and descent speeds were expressed by the same speed profile, say the same calibrated airspeed, was, in terms of transit fuel consumption and cost, very close to the corresponding minimum.

An example of this is given in Figure 5(a) from Reference 12, where the fuel versus time relationship for cr = de extends from e1 to e2. The maximum penalty in terms of fuel when operating in accordance with such a procedure instead of [F(t)]min is of the order of twenty kilograms, i.e. a quantity of the order of one percent of the fuel required for the transit from the entry point to the assembly point. It can be noted further that over an appreciable part of the interval available for potential control, namely from e1 to e2, the difference is appreciably smaller, being practically negligible betwen mf and e2.

2.5.1. Descent at high or maximum speed

During our investigations, it was observed that for some aircraft it was current practice to descend at rather high speeds. For example, when operating a DC-10 today, the general recommended descent speed is 320 kt-CAS, the maximum CAS being 340 kt. It is clear that for this particular aircraft the maximum descent CAS constitutes the minimum fuel profile if the transit time is to the left of a1 (See Figures 3(a) and 5(a)). In terms of consumption, the maximum descent CAS then departs progressively from the minimum fuel profile, as the cruise speed decreases, to reach a maximum deviation at point c. Accordingly, a high descent speed or the maximum descent speed can be justified in terms of consumption, only if the cruise phase is also performed at very high speed as is clearly shown in Figures 3(a) and 5(a); in other words when the transit time is relatively short, that is to say near a1.

When compared with the smooth transition profile (See Figure 5(a)); descent at high speed is advantageous only where the transit time is less than that at point g; where the smooth transition curve intersects with the maximum descent speed curve. This is obvious but does not affect the general conclusions regarding the quality of the approximation resulting from the use of the smooth cruise-to-descent transition profile instead of the minimum fuel profile.

2.5.2. Possible amendment for aircraft operated economically at high descent speeds.

At first sight the observations made in the previous paragraph may appear different for aircraft such as type 2B (Hawker Siddeley Trident 3B), which exhibit a fuel-time relationship as illustrated in Figure 5(b). In this figure, in addition to the following specific profiles :

(a) minimum and maximum cruise speeds;
(b) minimum and maximum descent speeds;
(c) minimum fuel (time-constrained);
(d) smooth cruise-to-descent transition;

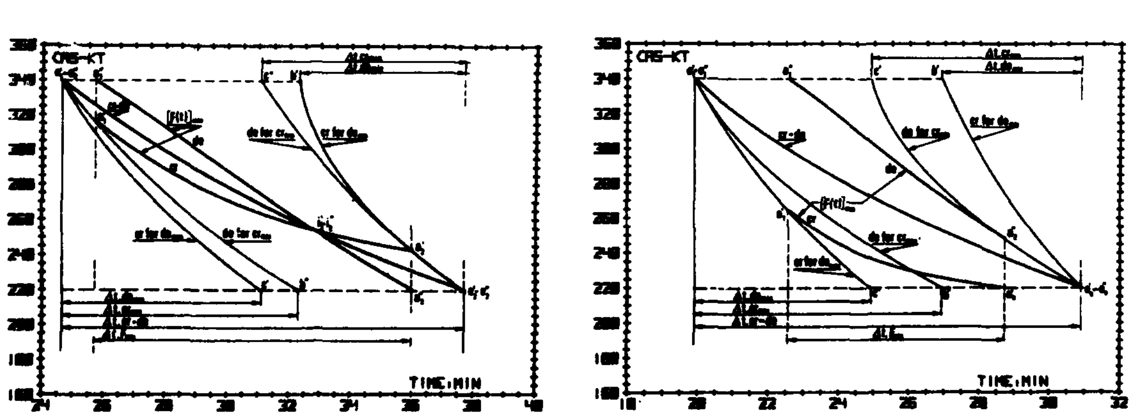
the profile defined by $(CAS)_{de} = (CAS)_{cr} + \Delta\ CAS$ (1)

has been drawn for cruise-to-descent differences of 10, 20, 30 and 40 knots. In this case, disregarding the energy required to create the variation in momentum, the maximum discrepancy between the minimum fuel profile and the smooth cruise-to-descent transition is of the order of 40 kg, that is to say some 3.8 % of the fuel required for the transit. In fact, these figures should be corrected since it became apparent that the theoretical maximum speed indicated here would not be used in practice, the usual descent speed being limited to 320 kt. This decreases the discrepancy observed from 3.8 to about 1 % .

Even so, in cases where maximum descent speed would be recommended, it would be appropriate to change the smooth cruise-to-descent transition profile to the profile defined by the above simple relationship. The magnitude of the acceleration would then possibly be adapted to the transit time required. If such a technique were to be used, profile definition would remain extremely simple, while the difference in consumption as compared with the minimum fuel profile would remain negligible, as the iso-acceleration profile curves indicate.

Another method of achieving the same effect as that resulting from relationship (1) is to specify the cruise and descent speeds in terms of a Mach/CAS profile. When considering a cruise level of 25,000 ft, a directive like cr = de = 0.70/340 would result in a 300 kt CAS cruise speed and a speed of 340 kt CAS during the major part of the descent.

However, at this stage of our investigation and principally for the reasons already mentioned, it is probably sufficient to limit the families of profiles considered to the smooth cruise-to-descent transition, i.e. the profile for which Δ CAS = 0.



(a) (b)

Cruise and descent components for typical inbound speed profiles

Figure 6

2.6 Cruise and descent speed components.

In terms of ground-based control, the zone of convergence concept integrates both phases, namely (a) the final part of the cruise or even the entire cruise and (b) the descent phase.

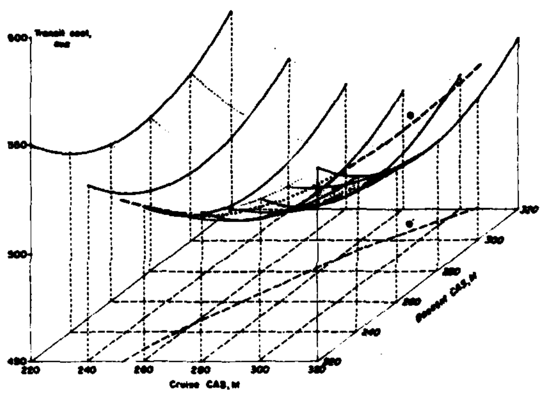
Consequently, whatever the criterion used for the definition of the transit speed profile or transit law, (e.g. minimum transit fuel consumption, smooth cruise-to-descent speed transition, constant CAS descent, etc.) it will necessarily be made up of two components : one associated with the cruise phase and the other with the descent phase. In the case of the smooth cruise-to-descent speed transition, these two components are by definition identical.

Once the criterion has been defined for transit through a given zone of convergence, the following ensues :

(a) the limits of the corresponding transit time range are determined;
(b) within this transit time range there is one, and only one, possible pair of speed profiles, i.e. one profile for the cruise and one for the descent, that can achieve a particular transit time.

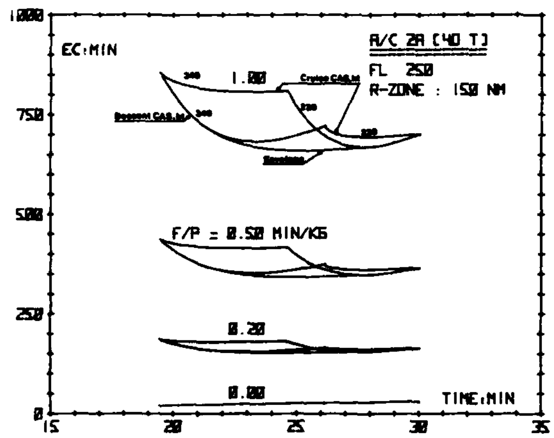
In Figures 6.(a) and (b) the cruise and descent components of the transit speed profile are shown for typical transit conditions.

For ease of reference, Figures 6(a) and (b), which give the cruise and descent speed law components, have been associated with Figures 5(a) and (b) respectively, showing the transit fuel consumption for the same transit speed laws.



Cost surface versus cruise/descent speed

Figure 7



Cost versus time for various cost ratios

Figure 8

Such pairs of diagrams clearly illustrate the control of individual aircraft in the context of the zone of convergence concept. As already implied when discussing the fuel-time relationship, where the transit time is constrained by Air Traffic Control, the only transit speed law to be considered is obviously the minimum fuel consumption transit or its practical approximation, namely the smooth cruise-to-descent speed transition law. Under the given condition of constrained transit time the minimum fuel speed law at the same time results in the minimum cost transit. The iso-extreme descent or cruise transit laws are given as convenient references : in addition, in most cases these constitute parts of the boundaries of the transit fuel-time domain.

2.7. Equivalent flight cost

2.7.1 Direct operating cost

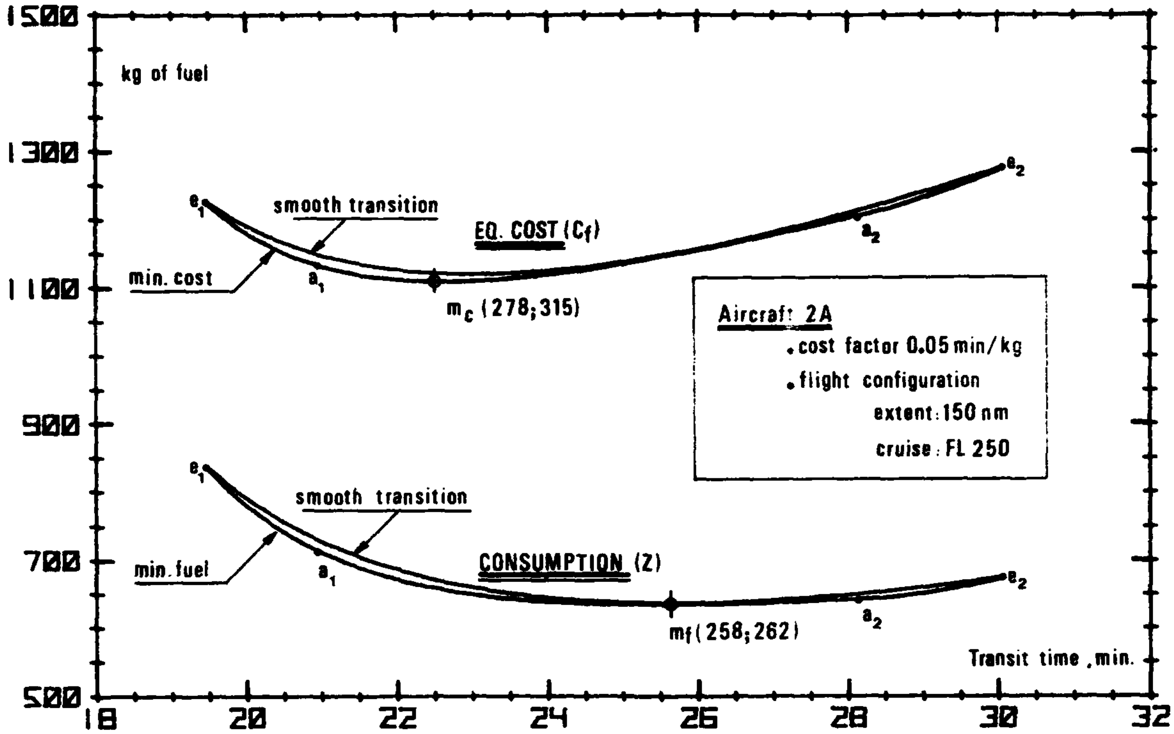
The direct cost of a flight (C) is essentially made up of two components, one corresponding to the total consumption of fuel required (z), the other increasing with the flight duration (t). If an average cost per unit of time of transit is defined and noted "p" and if "f" represents the cost of one unit of mass of fuel, the cost of the transit considered can be expressed in the linear form

$$C = z.f + t.p$$

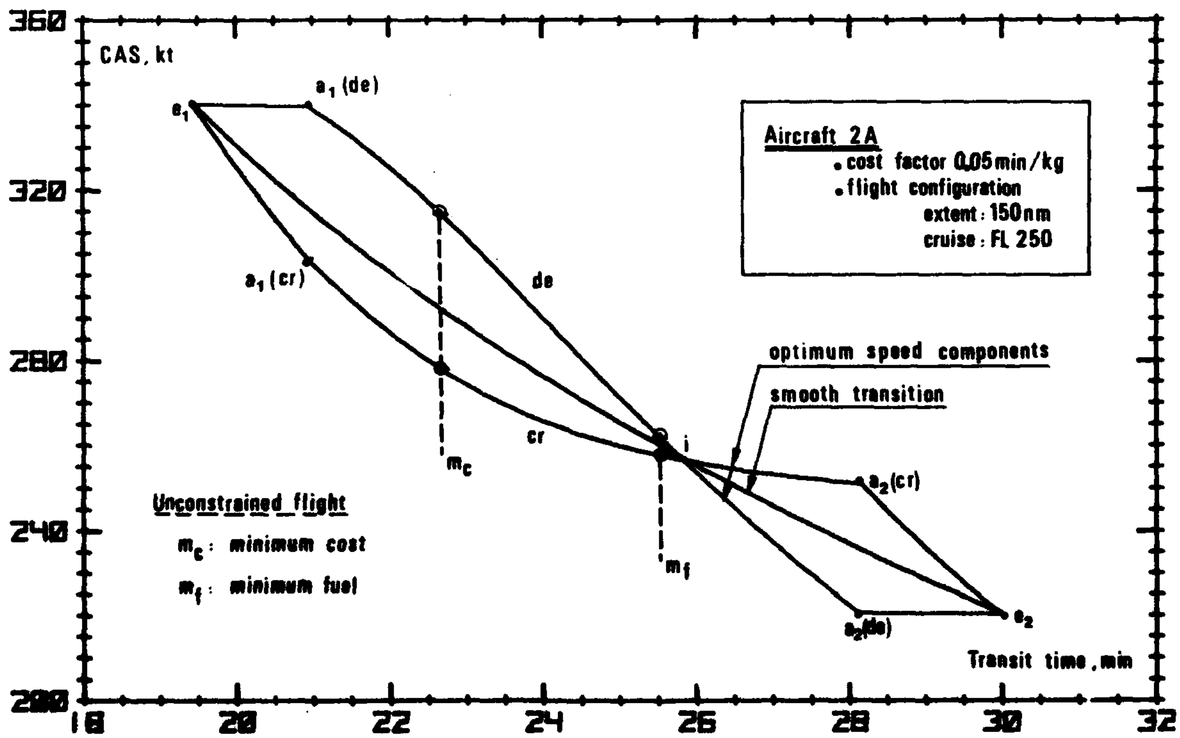
The quantity p is an economy characteristic of the aircraft, reflecting to some extent the financial philosophy of the operating airline. For air traffic control purposes, it is convenient to average p over the range of airlines and to introduce an equivalent transit cost in one of the forms

$$Ct = z.\varphi + t \quad \text{or} \quad Cf = z + t/\varphi \quad \text{with} \quad \varphi = f/p$$

where the quantity φ referred to as the cost factor, is the ratio of the unit-fuel-cost to the unit-flight-time-cost.



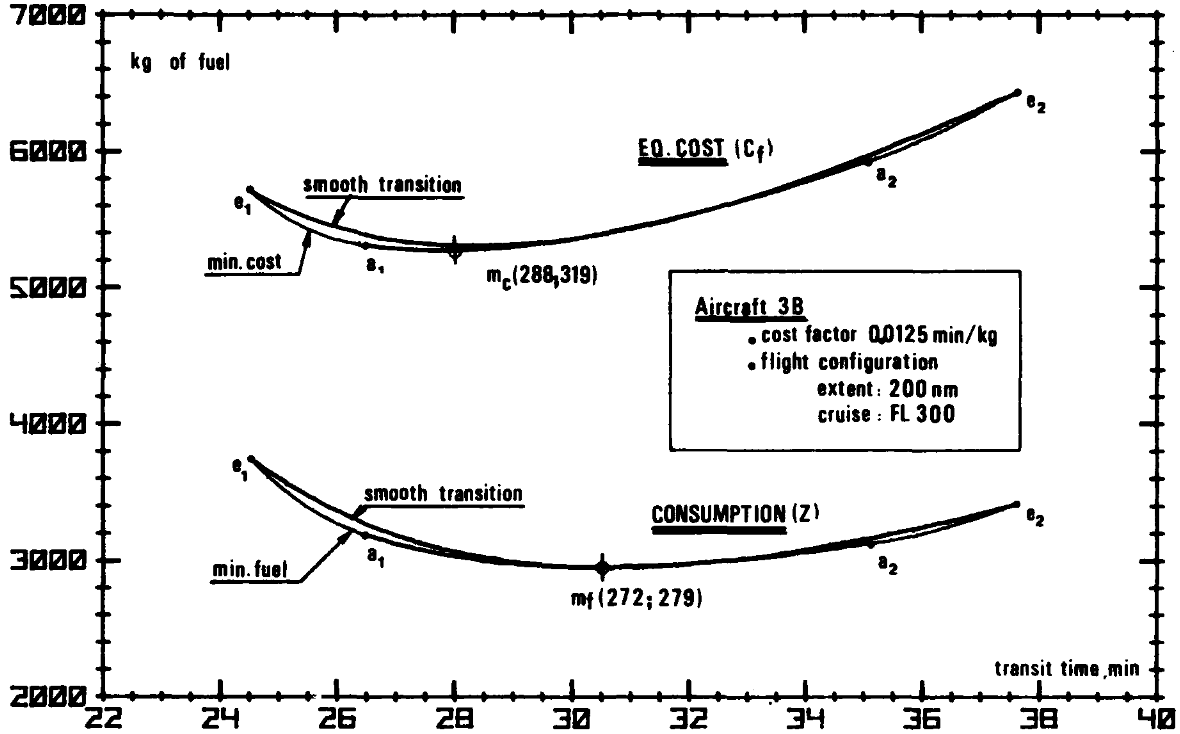
(a)



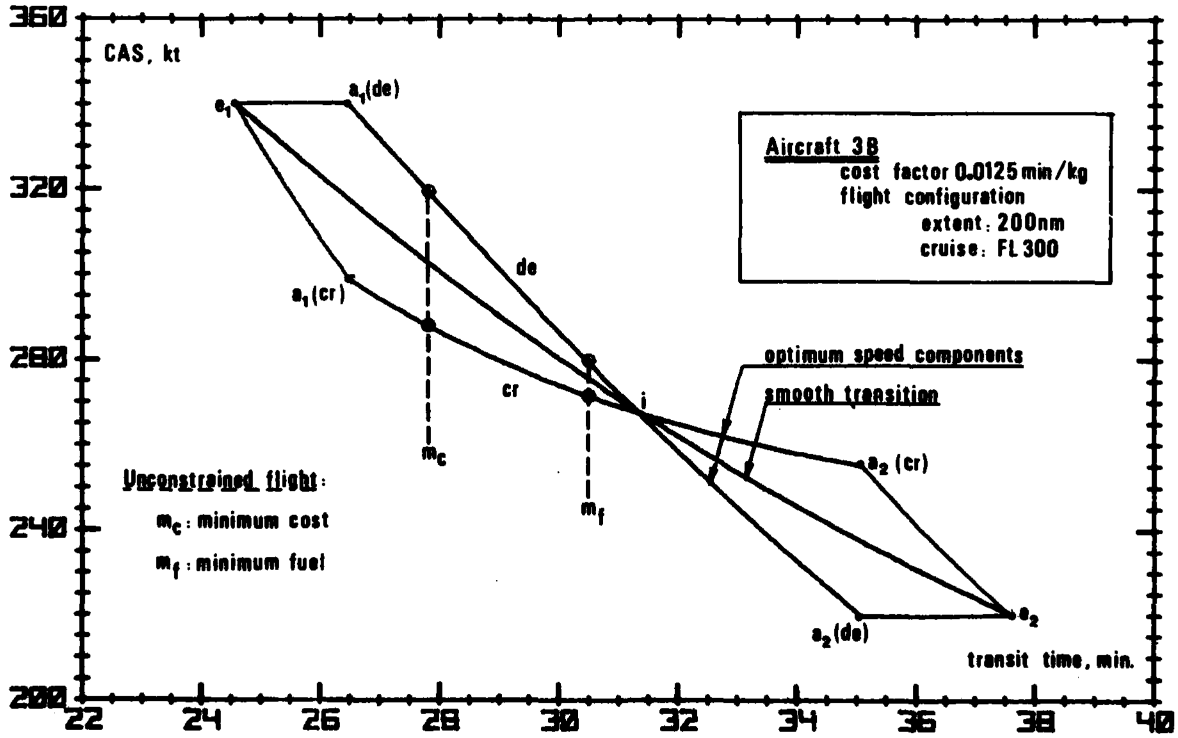
(b)

Selection of cruise/descent speed profiles for transit at minimum consumption or cost
(Short-haul medium weight aircraft)

Figure 9



(a)



(b)

Selection of cruise/descent speed profiles for transit at minimum consumption or cost (Long-range wide bodied aircraft)

Figure 10

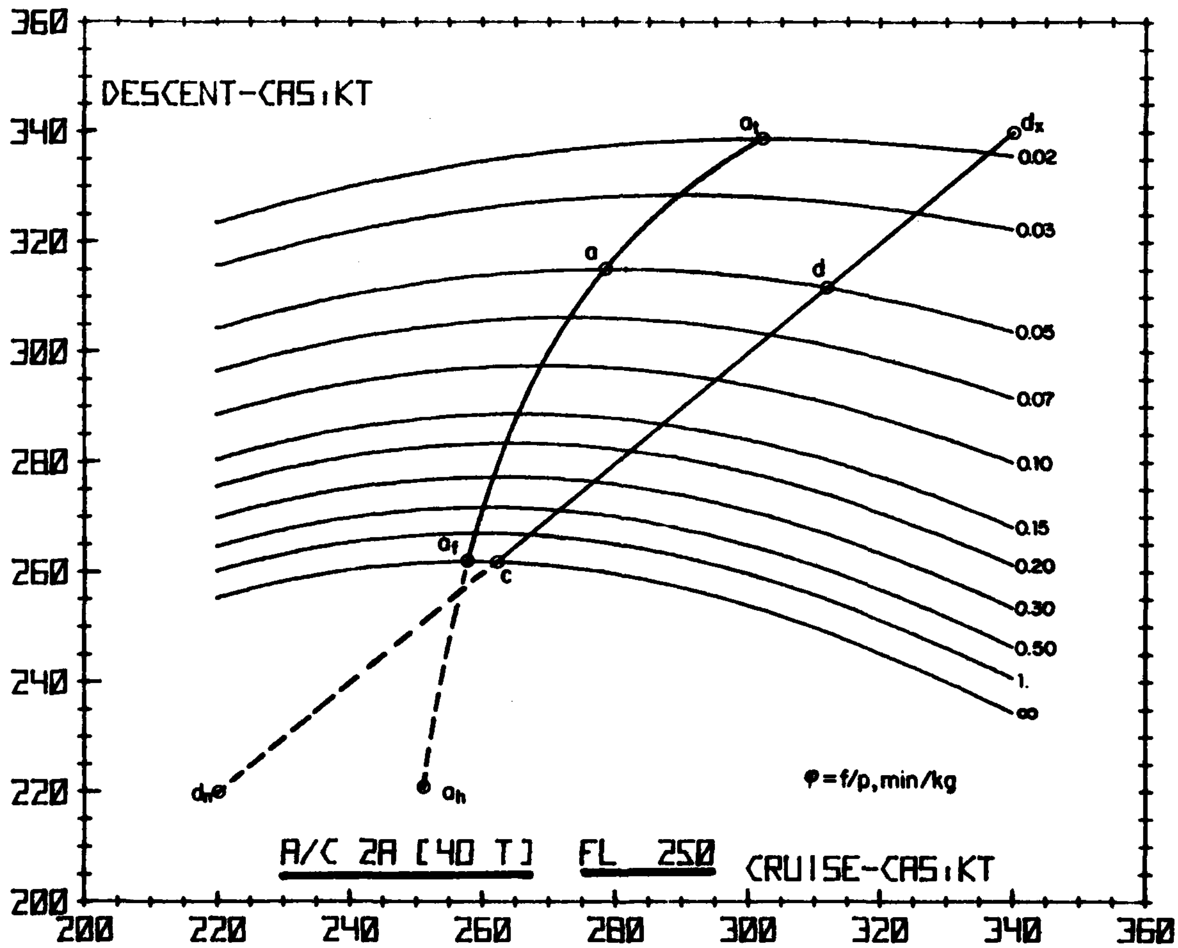
2.7.2. Transit cost versus time relationship

Once a pair of cruise and descent speed components is defined, the time and consumption for the transit are determined. Accordingly, the cost of the transit is also known. The relationship between the cost and time of transit is similar to the consumption versus time relationship illustrated in Figures 3(a), 5(a) and (b).

Using the equivalent cost Ct, the transit cost versus time relatonship appears as illustrated in Figure 7. This diagram corresponds to a short-haul aircraft of the Boeing B-737 family and a cost ratio f/p ranging from 0 to 1.00 min/kg. The present cost ratio for such an aircraft lies in the range 0.05 to 0.10 min/kg. A cost factor approaching infinity would correspond to an operating cost made up almost entirely (about 97 %) of the fuel component while the present situation shares, in average, practically equally the operating cost between time and consumption components.

The transit cost surface versus cruise and descent speeds is given in Figure 8. The lines marked "e" on the surface and "e'" in the speed plane correspond to the transit at minimum cost.

Expressing the transit cost in terms of mass of fuel and considering only the pairs of speed components of practical interest, the cost-time relationship appears as shown in Figures 9(a) and 10(a) for a short-haul, medium-weight aircraft (2A) and for a long-range wide-bodied aircraft (3B) respectively. The corresponding fuel-time relationships are also shown, while the associated cruise and descent components are given in Figures 9(b) and 10(b). Furthermore, the diagrams raise a few points which will be discussed in the next paragraphs.



Summary of optimum cruise/descent speeds

Figure 11

2.8 Selection of transit cruise/descent speed components.

The selection of an optimum cruise/descent profile (either minimum fuel or minimum cost for the transit) was discussed in Reference 13. Some of the conclusions reached are summarised hereafter (see Figure 11) :

(a) The optimum profile is composed of two basic speed profile components, one for the cruise, the other for the descent;

(b) Since these two profiles are generally distinct, they imply a transition (acceleration or

deceleration) phase between cruise and descent;

(c) The minimum (minimorum) consumption profile is independent of the extent of the cruise-descent segment;

(d) For minimum cost operation, this profile depends on the unit-fuel-cost to unit-flight-time-cost ratio only;

(e) Where a flight is time-constrained, for instance by Air Traffic Control as a result of the traffic situation, the minimum fuel and minimum cost profiles coincide;

(f) The introduction of the smooth cruise-to-descent speed transition law (Ref. 12 and Section 2.5) constitutes a practical implementation of the minimum cost/fuel transit speed profiles.

(g) Further, the possibility of a constraint on one of the two speed components cannot be discarded.

These general conclusions will now be discussed in more detail.

OPTIMUM CR / DE PROFILES

Min Cost	: (v_{cr}, v_{de})
Min Fuel	: (v_{cr}, v_{de})
Min Cost at v_{cr} !	: v_{de}
Min Cost at v_{de} !	: v_{cr}
Min Fuel at v_{cr} !	: v_{de}
Min Fuel at v_{de} !	: v_{cr}
Min Cost / Fuel at t !	: (v_{cr}, v_{de})
Quasi min C/F at t !	: $(v_{cr}, v_{de} = v_{cr})$

Transit criteria/constraints and selection of cruise/descent speed components

Figure 12

The cruise-descent speed profile corresponding to any combination of the transit critera and constraints (see summary in Figure 12) is readily determined, especially when the aircraft performance information is available in the PARZOC form (Refs. 8 and 13). Based on the data presented in Reference 7, the selection of flight conditions was discussed in References 14 and 15, in which consumption and cost, respectively, were used as basic criteria. The range of aircraft considered (see Table 1) extends from a light-weight short-haul aircraft similar to the Fokker F-28 to wide-bodied long-range aircraft representative of the McDonnell Douglas DC-10 and Boeing B-747 aircraft. Further to the general conclusions already mentioned, the discussions lead to the following remarks :

(a) For a given aircraft cruising at a particular altitude, the minimum minimorum cost profile depends only on the fuel-to-time cost ratio f/p.

(b) Both cruise and descent speed components decrease when this ratio increases.

(c) The rate at which the speeds decrease when this ratio increases varies considerably from one aircraft type to another as does the range of possible speed variation corresponding to a given f/p-interval.

Figure 11 is a typical illustration of an average medium-weight short-to-medium-haul aircraft (similar to the Boeing B-737, at 40 tons landing-weight). The fuel-to-time cost ratio, f/p expressed in minutes of flight per kilogram of fuel, ranges from 0.02 to infinity. The locus of minimum minimorum cost cruise/descent speed combinations as a function of the f/p ratio corresponds to the curve (af,a,at). The diagonal corresponds to the smooth cruise-to-descent transition.

The descent speed component minimising the transit cost (or transit fuel) when the cruise speed is fixed, is unique. In contrast, there may be two acceptable cruise components minimising the transit cost (or transit consumption) when the descent speed is constrained. At the limit, when the fuel-to-time cost ratio (f/p) approaches infinity, the minimum cost and minimum fuel cruise/descent speed profiles coincide.

The locus of cruise and descent components which minimize the cost and/or fuel for a given time of transit corresponds to the envelope of the cost- (or fuel-) time relationship (Figure 11). Accordingly, in that case within the allowable direct transit time range, there is a single pair of cruise and descent speed components which minimises simultaneously the transit cost and consumption. Further, in the (cruise CAS, descent CAS)-plane, the loci of pairs of cruise-descent components for minimum minimorum transit cost

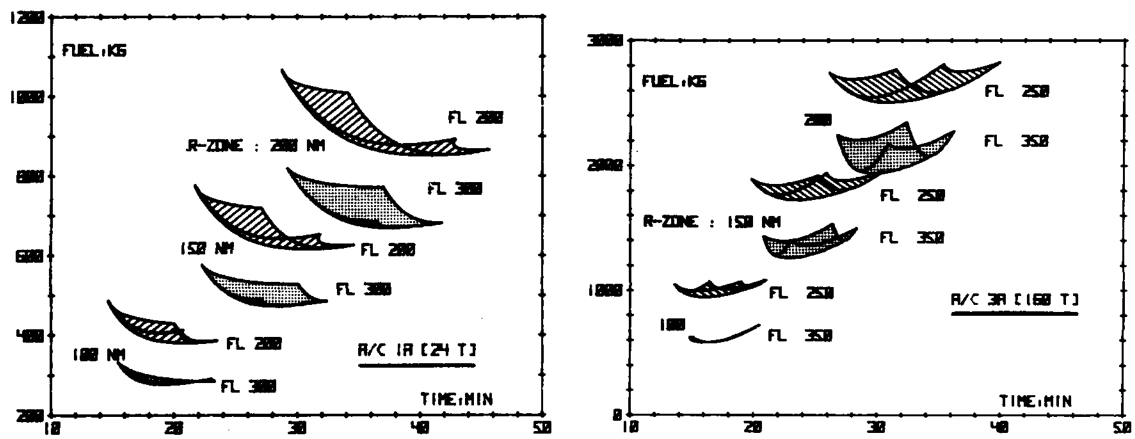
and minimum cost at imposed transit time coincide, of course, in the common speed range (see Fig.11, an-at).

Additionaly, it should be noted that the cruise and/or descent components corresponding to minimum cost (or fuel) and unconstrained by the time of transit, are independent of the zone extent. The same applies to the pairs of cruise and descent speed components defining the locus of the cost- (or fuel-) versus time relationship. Of course, when using the smooth cruise-to-descent speed transition procedure, flight distance still has a slight effect on the common cruise/descent speed for minimum cost or consumption transit.

2.9. Influence of flight conditions

2.9.1. Influence of the extent of the control zone

It has already been shown how the extent of the segment affected both the transit time control range and the related consumption for direct flights (Fig. 4(a) and (b)). This is now presented for the entire allowable speed range in Figures 13(a) and (b), for a light-weight short-haul aircraft and a wide-bodied long-range aircraft, respectively. The detailed effect of the extent of the zone on the fuel consumption versus time of transit and on the selection of speed components when the transit is time-constrained, is presented in Figures 14 and 15 for a medium-weight short-to-medium-haul aircraft. Figure 14 gives the consumption versus time of transit for two families of speed profiles, namely minimum consumption (A and D) and smooth cruise-to-descent transition (B), for flight distances ranging from 100 to 300 nm, the cruising altitude being taken to be equal to 25,000 ft. Interval "A" pertains to the true envelope while "D" corresponds to the maximum acceptable descent speed.



(a) (b)

Range of transit time and consumption

Figure 13

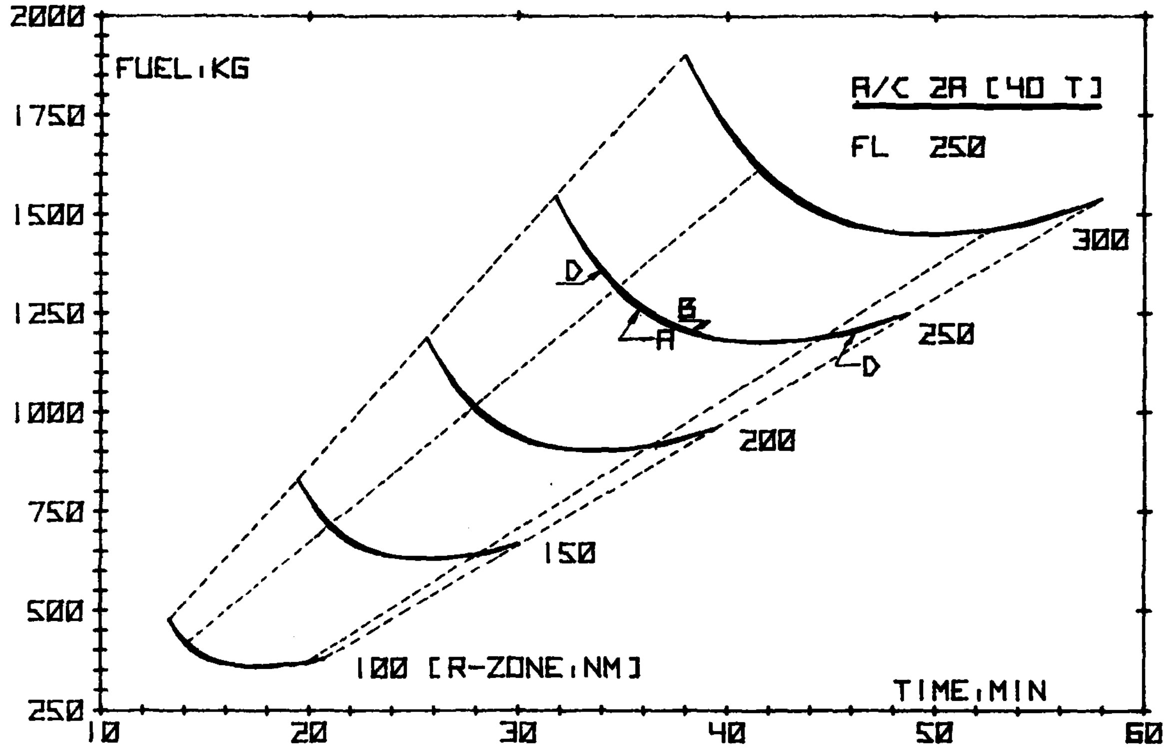
The effect on the selection of cruise and descent speed components is clearly shown in Figure 15. The speed profiles corresponding to the minimum minimorum for both cost and consumption are independent of the extent of the zone as already indicated.

To take a particular transit, designated "p" on the diagram, for a zone extent of 100 nm, the corresponding cruise and descent components of the minimum fuel transit law are 295 and 267, kt respectively, while the common value for the smooth cruise-to-descent speed transition is an intermediate value of about 284 kt. The family of minimum fuel transits characterised by the same relative position on the fuel-time diagram, namely by the same cruise and descent components, are approximated by a family of smooth cruise-to-descent profiles (p) characterised by a common value for both cruise and descent speed phases.

As the zone extent increases, the cruise component has an increasing greater impact on the transit time. The result of this is that, in the particular example presented in Figure 15, the (ps) speed tends to decrease and approach (i2) as the extent of the zone increases. Similarly, for transit times greater than t(i2), (ps)-speed increases to approach (i2). Since i2 corresponds to a coincidence of minimum fuel and smooth cruise-to-descent profiles, it is expected that the relative difference between the two profiles for similar transit times will decrease as the zone extent increases.

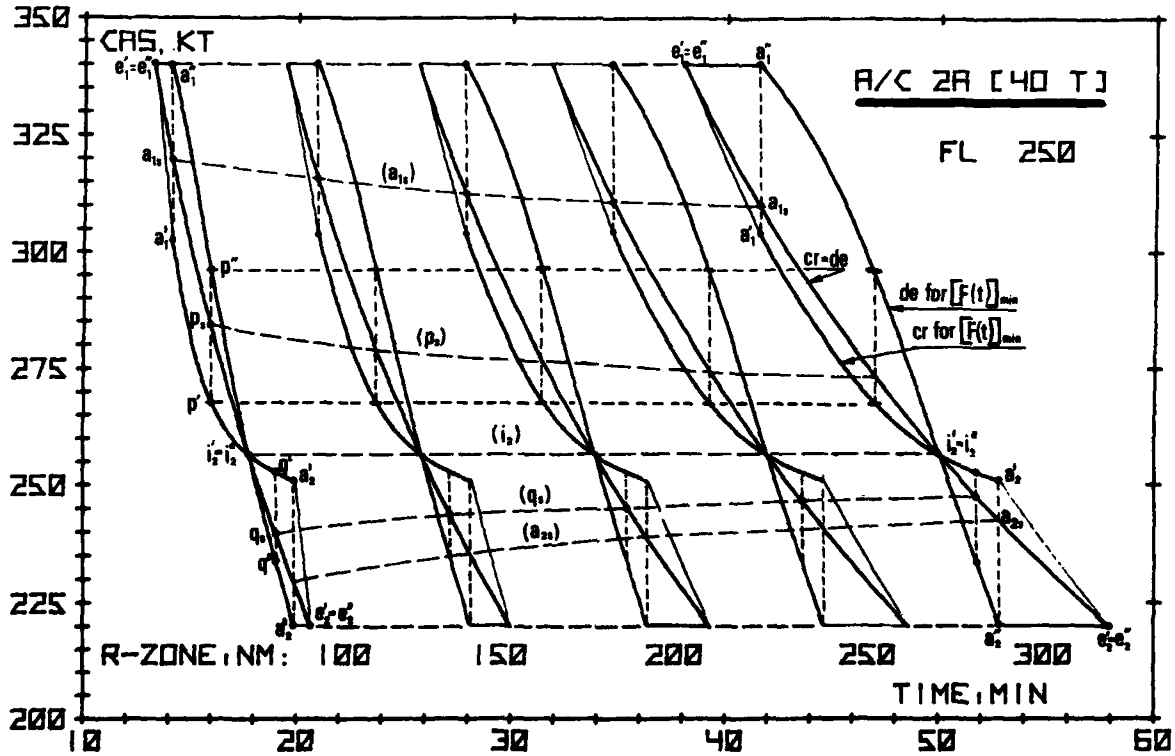
This is illustrated quantitatively in Table 3 in the case of a light-weight short-haul aircraft for which both limits a1 and a2 are within the operational range. The aircraft enters at FL 250, the flight distance ranging from 100 nm to 400 nm in steps of 50 nautical miles.

The table gives the time and consumption corresponding to transit points a1 and a2, together with the extra fuel required to implement the smooth cruise-to-descent speed transition law. This difference although increasing in absolute terms in proportion to the zone extent (from 11 to 18 kg for transit at



Influence of cruise/descent flight extent on the minimum-consumption versus time-of-transit relationship

Figure 14



Influence of flight extent on cruise/descent speed selection

Figure 15

time a1 and from 4 to 5 kg for transit at time a2), decreases appreciably in percentage terms (from 2.5 to 0.8 % at time a1 and from 1.2 to 0.3 % at time a2).

For a given transit time (within the operational time-of-arrival control range), the calibrated airspeed defining the smooth transition law is intermediate to the cruise and descent components of the minimum fuel transit, which in some cases may differ appreciably. This is clearly shown in Figure 15, where the difference between cruise and descent CAS reaches 40 knots.

Table 3 gives an indication of the respective values of the speeds characterising the two transit procedures for the case of an aircraft 2A similar to the Boeing B-737 entering at FL 250. For each zone extent, the speed components are given for both limits (a1 and a2) of the envelope.

From the point of view of speed profile definition, the smooth cruise-to-descent speed transition law is certainly advantageous. Indeed, both cruise and descent phases are characterised by the same speed profile (Mach number/calibrated airspeed) limited, in this paper, to the calibrated airspeed.

Zone extent (nm)	100	150	200	250	300	350	400
Cruise, Descent CAS (kt)							
for $ts = ta_1$	321	315	313	311	310	309	308
for $ts = ta_2$	229	235	239	241	242	243	244

Flight configuration

Aircraft : medium-weight, short-haul (2A)
Cruise altitude : 25,000ft
Lower limit (a1) : Cruise CAS : 304 kt; Descent CAS : 340 kt
Upper limit (a2) : Cruise CAS : 251 kt; Descent CAS : 220 kt

Effect of ZOC extent on smooth transition speed components

Table 3

2.9.2. Effect of cruise altitude

Most of the analyses made so far and the results presented have related to a particular cruise altitude typical of the operation of the aircraft in question. This section summarises the influence of altitude on the fuel versus time relationship and on the comparison between the smooth cruise-to-descent speed law and the "minimum fuel" transit law.

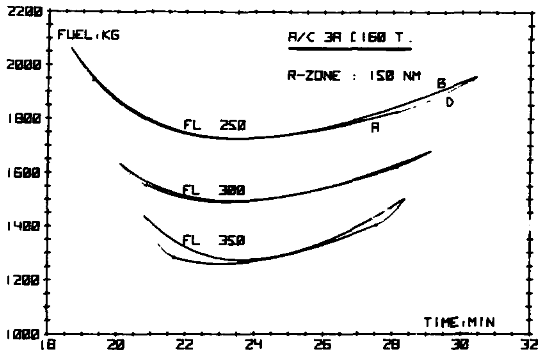
The effect on the consumption versus time relationship is shown in Figure 13 for two radically different aircraft, one similar to the Fokker Fellowship F-28, the other representing the wide-bodied Boeing B-747 category.

An increase in cruise altitude will normally decrease the transit consumption, the cruise and descent speed components being adjusted accordingly. This property of the absolute minimum transit consumption remains valid for both the minimum fuel when time constrained and the smooth cruise-to-descent speed transit laws. Nevertheless, the effect may be different from one transit law to another. In Figure 16 this effect is illustrated for a wide-bodied aircraft of the McDonnell Douglas DC-10 family over a segment of 150 nm. The three altitudes considered range from 25,000 to 35,000 ft in steps of 5,000 ft. Figure 16 shows the influence of altitude on transit consumption, while Figure 17 illustrates the shift in speed for both the minimum fuel transit and the smooth cruise-to-descent transition laws.

From these results, it would seem that altitude has little effect on the comparison between minimum fuel and smooth cruise-to-descent transition profiles. The difference is slighter when the cruise is conducted at a lower altitude, that is to say in a region where the consumption is higher. At higher altitude, the discrepancy between the two transit laws tends to increase, particularly in the fast transit area, to reach a maximum value of the order of five per cent at maximum descent speed. In absolute terms, this maximum discrepancy is of the order of 60 kg. It will be seen that this amount constitutes the upper bound for the differences observed in all the configurations (aircraft, altitude, speed) considered. However, when the smooth cruise-to-descent transit speed profile is defined in terms of the usual

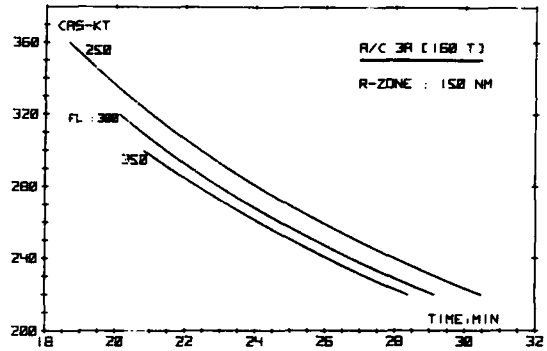
combination of Mach/CAS values, rather than CAS only as it was the case in the example given above, the discrepancy observed at high altitudes and speeds will be reduced to the same level as is obtained for lower cruise levels.

To assess the influence of altitude in a variety of practical cases, the five aircraft listed in Table 1 were then operated over a 150-nm segment at three different altitudes, namely the average cruise altitude considered previously and two additional levels located 5,000 ft below and 5,000 ft above. This comparison is made throughout the acceptable operational speed range for the three cruise altitudes selected.



Effect of altitude on minimum consumption

Figure 16



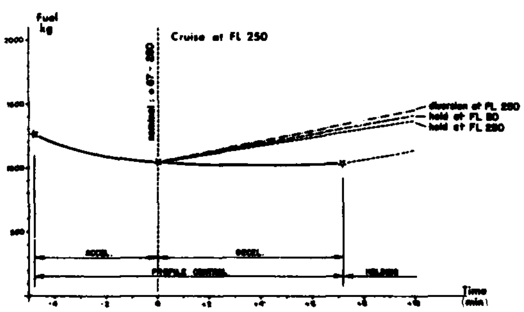
Effect of altitude on speed selection

Figure 17

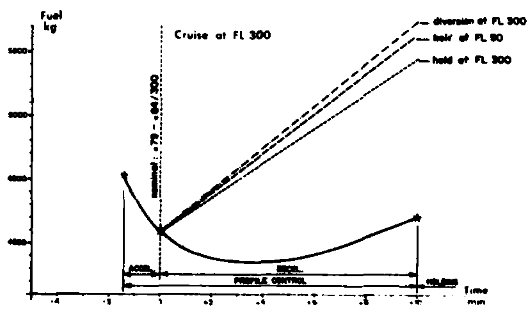
In general, it can be stated that within the cruise altitude band considered, mainly 20,000 to 30,000 ft for aircraft 1A, 2A and 2B and 25,000 to 35,000 ft for aircraft 3A and 3B, the cruise altitude only slightly affects the result of the comparison between the minimum fuel and smooth cruise-to-descent speed transition laws.

3. CONTROL OF TIME OF ARRIVAL

In today's operation, sequencing, i.e. the allocation of landing time-slots, usually results from an organisation process conducted mentally with of without computer assistance. The main criterion, after safe conduct of the flights, is the maximum use of the runway capacity available. In the Zone of Convergence concept, the organisation consists of an automatic optimisation with a view to meeting specific objectives such as minimum total consumption or cost for the whole of the traffic considered.



(a)



(b)

Comparison of cruise/descent profile control with current practice

Figure 18

For individual aircraft, this results in the allocation of a specific transit time from the entry into the zone to touch-down. In general, when a flight is inbound to a congested terminal area, this transit time will differ from the preferential one, with time requiring to be either gained or lost.

3.1. Control of transit time

A transit time shorter than the nominal one can be achieved by acceleration from the nominal transit speed. The maximum time wich can be gained is limited by the maximum allowable operational speed of the aircraft. If the arrival of the aircraft is delayed b· Air Traffic Control the excess time can be spent in various ways :

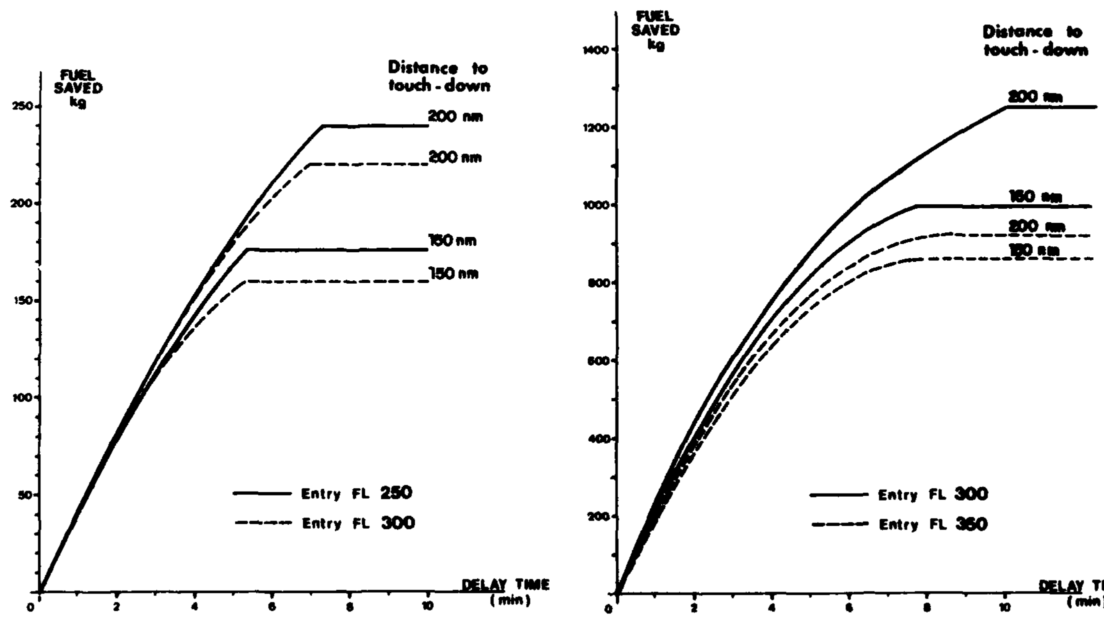
(a) diversion at cruise level;
(b) holding at cruise level;
(c) path-stretching at low altitude;
(d) holding at low altitude, e.g. FL 50;
(e) speed profile control.

When the transit time is being controlled through cruise/descent speed profile control, the maximum delay that can be accommodated in this way in a given zone extent is limited by the slowest allowable operational speed of the aircraft. If more time should be lost than this maximum, the remaining time must be consumed through application of one of the other methods.

3.2. Fuel consumption and transit time

As discussed in the previous section, the fuel consumed in the zone by a given aircraft will vary with the time of transit. In particular, using the preferential profile as a reference, fuel consumption will depend on the deviation (advance or delay) from the preferential transit time as imposed by Air Traffic Control. This is illustrated in Figures 18(a) for an aircraft of the Boeing B-737 family and (b) for an aircraft of the class 3B (similar to a Boeing B-747 type) for a flight distance of 200 nm. The diagrams show the fuel consumption associated with four of the techniques mentioned above. Although currently applied, path-stretching at low altitude has not been explicitly considered in view of its high cost.

When the excess time is spent using diversion enroute or holding techniques, whether at high or low altitude, the total amount of fuel required for the transit increases linearly with excess time. The rate of increase depends on the altitude and on the speed at which the excess time is spent.



(a) (b)

Benefits resulting from the use of cruise/descent profile control as against holding at cruise altitude

Figure 19

The nominal preferential speed profile associated with minimum cost is at present usually faster than the minimum minimorum fuel transit speed. As a result, delays imposed by Air Trafic Control may lead to reductions in fuel consumption for individual aircraft (delays of up to about 8.5 minutes in the illustration given in Figure 18). Obviouslsy, if the airline's preferential profile were to coincide with the minimum minimorum fuel transit speed law, any transit time deviation required by Air Traffic Control would necessarily lead to individual increases in consumption.

In addition, since the nominal, preferential speed profile is usually faster than the operational minimum allowable speed, a considerable amount of fuel can be saved by decelerating and transiting at reduced speed instead of holding, even at high altitude , as is clearly shown.

3.3. Limitation of control range

The operational speed range governs the range available for the control of the time of arrival. This increases with the extent of the zone. Nevertheless, if the distance from entry to touch-down characterises the zone extent, only part of it is actually available for control, that is to say the cruise phase less an

initial decision buffer of some 10 to 20 nm, and the enroute descent phase, excluding approach and landing phases. Accordingly, the distance over which speed control can be exercised may be roughly 30 to 50 miles shorter than the total route length in the zone.

As an example, for a wide-bodied aircraft of the Boeing B-747 category, over a route length of 200 nm, the transit time may vary between 28 and 42 minutes and the transit fuel required from 3,450 kg to 4,830 kg, depending on the entry cruise level and transit speed, showing a difference of 40 % between the extreme transit conditions.

Zone extent (nm)	A/C 1A cruise level (FL)			A/C 2A cruise level (FL)			A/C 2B cruise level (FL)			A/C 3A cruise level (FL)			A/C 3B cruise level (FL)		
	200	250	300	200	250	300	200	250	300	200	250	300	200	250	300
100	115	84	(+)	109	109	(+)	22	(+)	(+)	324	(+)	(+)	726	(+)	(+)
150	142	134	106	162	162	164	89	70	28	399	419	321	782	782	698
200	153	167	114	173	173	181	117	112	84	436	466	363	827	852	732

(+) no speed control possible in the relevant zone extent because of the distance-to-descent required.

Fuel saved (kg) through speed control with respect to holding at cruise level

(delay period : 5 min.)

Table 4

3.4. Comparison of control of time of arrival techniques.

To cover a realistic set of flight conditions, five classes of aircraft currently operated in Western European airspace are considered (see Table 1).

For each aircraft class, the following have been computed :

(a) fuel-time relationship for the preferential speed profile (also called nominal profile);
(b) fuel-time relationship for the smooth cruise-to-descent speed transition law (or quasi-optimum);
(c) comparison between cruise/descent speed profile control using the smooth cruise-to-descent transition law and other delaying techniques.

In each case, this information was generated for three zone extents and three cruise altitudes, as applicable. The resuslts presented in Reference 14 are summarised hereafter. The differences among conventional methods are relatively minor; holding at cruise altitude (using the aircraft's specific holding procedure) is slightly better than holding at low altitude (5000 ft) which, in turn, appears slightly better than path extention at cruise conditions. Path-stretching at low altitude is even worse and therefore does not figure in the diagrams.

In contrast, the difference between holding at cruise altitude and cruise/descent speed profile control using the smooth cruise-to-descent speed transition procedure is appreciable. Accordingly, it is only this part of the results obtained which is presented and discussed in this summary.

3.5. Absolute values of fuel saving through cruise/descent speed profile control.

The amount of fuel saved through the application of cruise/descent speed profile control using the smooth cruise-to-descent speed transition procedure rather than holding at cruise level is shown in Figure 19 for aircraft classes 2A and 3B. Data are presented for two typical zone extents, namely 150 and 200 nm, and two representative cruise altitudes, namely FL 250 and FL 300 for aircraft 2A, FL 300 and FL 350 for aircraft 3B.

These diagrams provide the following information :

(a) amount of fuel saved using cruise/descent speed profile control against holding at cruise altitude;
(b) time of transit control range available through trajectry control.

For aircraft class 2A of which the Boeing B-737 is a typical representative, Figure 19 shows that the fuel saving resulting from profile control to compensate for a five-minute delay is of the order of 200 kg in the altitude (FL 250-300) and zone extents (150-200 nm) ranges considered. For wide-bodied long-range aircraft, the amount of fuel which can be saved using profile control to adjust the time of arrival increases apreciably. To accommodate a five-minute delay, profile control would offer an advantage of about 400 (aircraft 3A) or 800 kg (aircraft 3B) over holding at high altitude in a 150-nm zone extent, when entering at FL 300.

Table 4 provides an overall idea of the savings which would result from the introduction of cruise/descent speed profile control using the convenient smooth cruise-to-descent speed transit procedure and summarises some of the results obtained. For a five-minute delay, it gives the absolute fuel savings in

kilograms obtained through speed profile control rather than holding at cruise altitude. The results are given for three zone extents, namely 100, 150 and 200 nm.

3.6. Fuel saving as a percentage of total consumption.

A comparison was made between the total transit fuel required when using smooth cruise-to-descent speed transition control to absorb a 5-minute delay and the fuel consumed during a transit at nominal speed followed by a 5-minute holding at cruise level for an intermediate zone extent of 150 nautical miles. The aircraft enters at an intermediate cruise level, namely FL 250 for aircraft 1A, 2A and 2B and FL 300 for aircraft 3A and 3B.

In the case of present commercial jet aircraft, the average transit time through a zone of 150 nm from entry to touch-down amounts to approximately 25 minutes. It is shown that for a 5-minute delay the application of cruise/descent speed profile control instead of holding at high altitude can save in the order of 25 per cent of the total amount of fuel which would be required for transit.

The particular results (only 5 % saving) obtained for aircraft of class 2B, of which the Trident 3B is the typical representative, are due to the specific characteristics of this aircraft. It is a representative of an older generation of aircraft particularly designed for high-speed operation. Therefore, it is most fuel-efficient at higher descent speeds and as a result speed control based on the smooth cruise-to-descent transition procedure using only the CAS as a indication of transit speed proves to be less efficient for such a type of aircraft. In fact the results could be improved considerably if the simple smooth cruise-to-descent speed transition law were to be slightly amended defining the transit speed law as a Mach/CAS combination as suggested in Section 2.

3.7. Transit cruise/descent speed control as against holding techniques : conclusions.

In traffic environments where aircraft cannot fly their preferential speed profiles due, for instance, to capacity limitations, cruise/descent speed profile control using the convenient smooth cruise-to-descent transition law constitutes a fuel-efficient transit procedure.

The benefits of such a scheduling control technique over conventional delaying procedures such as path-stretching, diversion at cruise conditions and holding at cruise or low altitude are assessed in range of flight configurations. In particular :

(a) the flight segment (cruise, enroute descent, approach and landing phases) extends over 100, 150 and 200 nm;
(b) the cruise altitudes considered include three typical levels separated by 5,000 feet;
(c) the aircraft considered constitute a sample representatve of the present fleet of turbojet aircraft operated in Western European airspace;
(d) the range of transit time control corresponds to the operational speed range practical for each aircraft concerned.

The comparison of both types of control procedures is made for the complete flight from entry into the zone to touch-down. The flight essentially includes the following phases :

(a) one-minute flight at cruise altitude after entry to allow the control to elaborate ZOC-directives and to permit the aircraft to establish an airspeed modification;
(b) the subsequent cruise phase followed by the enroute descent;
(c) conventional approach and landing for which a 20-nautical mile segment is foreseen.

For the control of the time of arrival, the transit speed law selected is characterised by the smooth cruise-to-descent transition, that is to say both cruise and enroute descent phases are defined by the same speed profile (Mach number/calibrated airspeed). The profile used to determine the nominal transit is the reference profile recommended by a representative European airline for the operation of the aircraft at the time of the investigation.

The control of the arrival time of each individual aircraft is made in accordance with air traffic control practice. The use of cruise/descent speed profile control is compared in terms of fuel consumption with conventional delaying techniques over the operational control range. The conclusions of the study include :

(1) The three conventional techniques considered are about equivalent in terms of fuel consumption, although holding at cruising level is slightly less penalizing than holding at low altitude which in turn requires some less fuel than a diversion at cruise conditions. For this reason, the subsequent comparisons will be made with holding at cruise altitude.

(2) Conventional delaying techniques require appreciably more fuel than cruise/descent speed profile control.

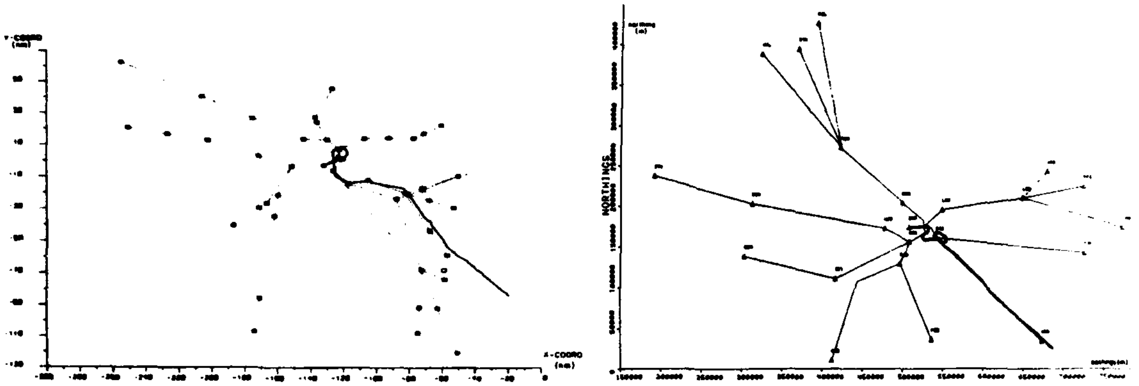
(3) The economy resulting from the use of profile control is expressed quantitatively over a wide range of flight and control configurations. It varies with cruise altitude and increases with the extent of the zone.

(4) The efficiency of cruise/descent speed profile control over conventional delaying techniques is illustrated by the following example : Over a 150-nm segment (from entry to landing); and a control of the arrival time aiming at producing a 5-minute delay, the saving of fuel would be of the order of 25 % of the total fuel required to transit through the zone, delay included. This means some 130 and 780 kg for aircraft of the types Fokker F-28 and Boeing B-747, respectively.

4. POTENTIAL SAVINGS IN AN EXTENDED TERMINAL AREA

4.1. Estimates of nugatory consumption

In the previous section, a preliminary step was undertaken to assess the benefits which should result from the use of trajectory control in an extended area. From the analysis made, it appeared that in a zone extending over 150 nautical miles, the benefits achievable amount to some 25 % of the consumption, for average ATC-imposed delays of the order of 5 minutes.

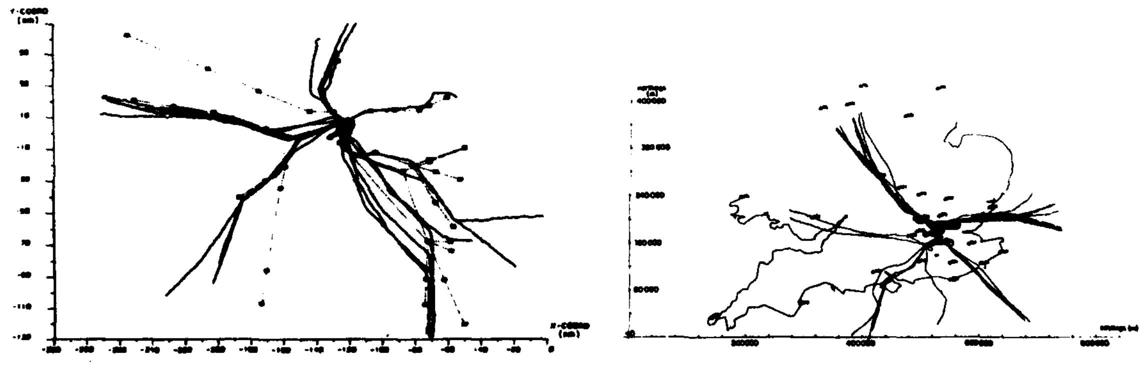


(a) (b)

Configuration of routes inbound to Brussels-National and London Heathrow

Figure 20

In order to obtain a practical estimate of such benefits in real life, two collections of flight data (radar, flight plans, landing time, wind and temperature) were organised in cooperation with the Belgian (RVA/RLW) and United Kingdom (CAA/NATS/ATCEU) Air Traffic Control authorities. Meteorological information was provided by the ATC Authority (RVA/RLW) for Belgium and by the Meteorological Office, Bracknell, for the United Kingdom. The samples of actual flight data collected are presented in References 16 and 17 for Belgium and the United Kingdom respectively. The method and technique used to derive the trajectory state variables and consumption information are described in Reference 18. The detailed results for the two areas covered are given in References 19 and 20. The following paragraphs summarise the approach followed and conclusions reached.



(a) (b)

Illustration of flights inbound to Brussels (a) and to London (b)

Figure 21

4.2. Geographical areas and traffic samples

These two typical geographical areas were selected deliberately, Brussels being an example of a medium-density terminal and London, one of Europe's highest-density ones in Western Europe. The general structure of the zones considered as derived from te observations is shown in Figures 20(a) and (b) for the Brussels and London areas respectively. Each of these diagrams also shows the horizontal view of a typical trajectory, while Figures 21(a) and (b) give the same view for a larger part of the traffic samples considered. The density and evolution of the samples are shown in Figure 22. Both samples have a duration of about two hours, slightly more in the case of the flights inbound for London Heathrow, slightly less in the case of those inbound for Brussels.

The maximum number of aircraft heading simultaneously for the terminal is eight in the case of the

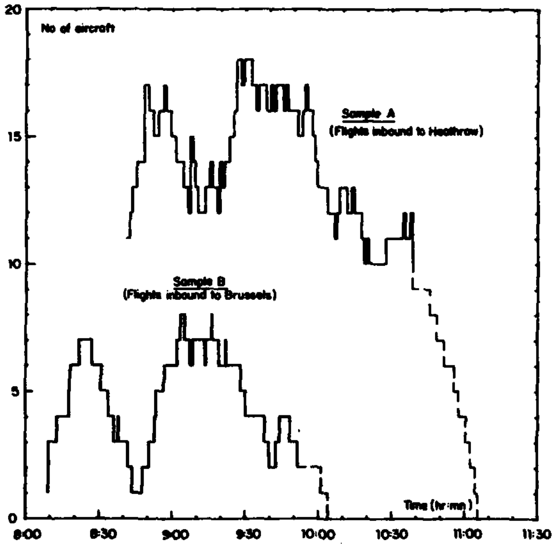
Brussels area, and eighteen in the case of the London zone.

4.3. Consumption of fuel

Using the method described in Reference 18, the amount of fuel burnt by each aircraft from entry to landing was estimated for those phases covered by the sample duration. The total consumption in the area for the inbound traffic is then obtained by summation extended to all flights concerned; for these two-hour samples it amounted to some 75 tons in the London area, (flights inbound to Heathrow only) and 15 tons in the Brussels area.

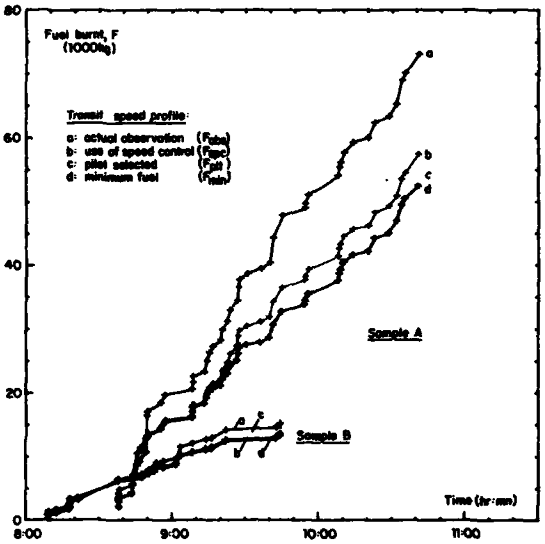
The consumption trend throughout the sample is shown in Figure 22, curve (a). This curve represents the fuel consumed in the area by those aircraft inbound to the airport concerned (Brussels or London Heathrow) between the beginning of the sample and the time considered.

The question now is what fraction of this consumption could be saved, and which technique would be most effective in achieving the expected result ?



Evolution of inbound traffic density

Figure 22



Fuel burn in extended terminal areas

Figure 23

4.4. Upper bound of potential benefits

The minimum (minimorum) amount of fuel required for the transit of all aircraft would be obtained if each flight were performed on the minimum consumption profile corresponding to the entry altitude. These consumption values have been computed and presented as curves (d) in Figure 23. Expressed in relative terms, the difference for the complete sample is of the order of 14 % in the Brussels area and 30 % in the London zone.

These savings can certainly not be achieved in practice, but in the subsequent paragraphs, possible control of the flights to improve the present situation is suggested.

4.5. Reference profiles selected by operators

The operator's recommended profile generally differs from the minimum consumption profile, since it is usually aiming at minimising the flight cost rather than consumption only.

For the sake of consistency, the recommended profiles used here, were determined from the observations made along the cruise and the upper part of the descent portion of the flight from entry into the zone until noticeable intervention of Air Traffic Control occurred. In this respect, due to the length of the routes in the zone, this determination was found to be more reliable in the London zone than in the Brussels area.

The consumption data corresponding to such profiles appear as curves (c) in Figure 23. Obviously these consumptions are slightly higher than the minimum ones shown as curves (d).

In view of the traffic situation these profiles may have to be altered by the ground-based control. Would it be possible to alter them in such a way as to meet the runway capacity constraints while reducing the total consumption, and as a result the overall cost, in the area considered ? Firstly, we shall consider the application of cruise-descent speed profile control as discussed in Section 3, then the essential principles of the Zone of Convergence (ZOC) concept suitable for implementing such a technique

will be presented in Section 5.

4.6. Cruise/descent speed profile control

In the London area, an appreciable number of aircraft have been ordered to hold at the assembly points, near the runway, as some may be seen from illustrations appearing in Figure 21.

With the observed arrival time sequence kept unchanged, cruise/descent speed profile control is used within the acceptable operating range to direct the aircraft from their entry into the zone to the runway in accordance with the principles discussed in Section 3. In other words, the sequencing and scheduling actually observed as resulting from the human controllers' action is maintained, but the control of trajectories, cruise and descent speed components only will cancel or appreciably reduce the holding delays.

The resulting consumption is illustrated by curve (b) in Figure 23. In this case, the time of transit is maintained as actually determined by the controller feeding the runway. Consequently, the reduction in consumption resulting from the use of trajectory control also constitutes the reduction in flight cost.

When expressed in relative terms, the savings made amount to 12 and 25 % of the present consumption in the Brussels and London areas, respectively.

4.7. Consequences

From these two experiments, it would appear that cruise/descent speed profile control of aircraft constitutes a major contribution to the reduction of excess consumption. This result is in line with the conclusions of the analysis made in Section 3, where similar savings were noticed for delays of 5 minutes for flights extending over some 150 nm (from entry to touch-down). The implementation of such control techniques will essentially require the definition of aids in order to :

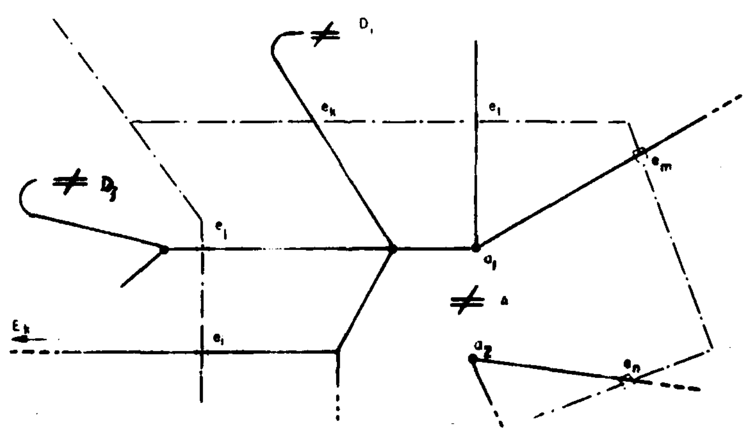
(a) determine the sequence of times of arrival at the runway;
(b) define and relay to the aircraft the relevant control directives.

These two aspects will be discussed briefly in Section 5 and 6. It is also worth noting that from the observations made, a scheduling defined to maximise the use of the available runway capacity would probably make it possible to recover about 85 % of the total potential, whereas optimisation of the inbound traffic would contribute to only a small portion of the potential benefits.

5. ZONE OF CONVERGENCE CONCEPT

5.1. Air route structure

A schematic presentation of the route structure in a zone of convergence is shown in Figure 24. This takes into account the present configurations (examples of actual geographical situations are given in Figures 1 and 20) but assumes possible control of the arrival time at the assembly point f the destination airport.



Schematic route structure

Figure 24

In the diagram, the points marked "a" represent assembly points located some 20 nautical miles from the runway at an altitude of 5,000 feet. Points marked "e" represent the boundaries of the zone, i.e. the entries into the zone of routes connecting the adjacent zones to the destination airport A which is considered to be the "centre" of the zone.

The zone is essentially anisotropic, its dimensions varying along each route, thus reflecting the

actual geography of the area covered. Accordingly, for convenience, the average value of the e-a distances, duly weighted by traffic conditions and other local factors, is referred to as the radius of the zone, that is to say the mean distance over which control of the arrival time at the assembly point is effective. This distance constitutes a major feature of the concept. It actually governs the range of control available and, as a consequence, the degree of effectiveness of the concept itself. The relationship between the radius of the zone and the control potential has been discussed in Sections 2 and 3.

5.2. Basic concept principles

5.2.1. Criterion

The main criterion applied is minimum total transit cost, as defined by the operators, for all aircraft present in the zone. In low traffic density, this entails clearing pilots to fly in accordance with the preferential profiles recommended by their respective airlines. On the other hand, when runway capacity is almost saturated, the criterion calls for maximum use of available landing capacity, while still, of course, keeping the global transit cost down to the minimum.

5.2.2. Conditions at entry

No particular requirement is imposed, nor is any assumption made regarding the distribution of the traffic at the points of entry into the zone, except for freedom from conflicts at the boundary. The traffic considered reflects the current situation. Future situations in particular geographical areas can, of course, be simulated insofar as the relevant traffic trends are defined.

On entry, the aircraft could be in cruise or descent phase, depending on a number of factors, particularly the cruise altitude and the remaining route length in the zone.

5.2.3. Available control and limitations

(a) Sequencing of landings

The reference landing sequence of aircraft is based on the times of transit from entry to landing as derived from the preferential profiles, that is to say those profiles which pilots would, whenever possible, follow to comply with the recommendations of their airlines.

Alteration of this sequence is considered, provided it remains within acceptable limits. Experience gained to date indicates that a maximum position shift of two units is reasonable from the point of view of both efficiency and individual acceptance.

(b) Control of scheduling

The time of transit can be controlled through certain variables, firstly the cruise and descent speed profiles and secondly, where the latter are not sufficient, holding at high altitude. If the aircraft is already descending at entry, then its descent speed should normally be maintained. If holding appears necessary it would be executed soon after entry.

(c) Range of transit time control

The range available for the control of the arrival time depends mainly on the operational speed range of each aircraft and the route length. These factors have been discussed in Section 2. As an illustration to be used later, Figures 25(a) and (b)* show the range of available control for the McDonnell Douglas DC-10 aircraft when entering at 30,000 ft. The time of transit is given in (a); point "p" represents the recommended profile. The range of control is of the order of one minute for possible advances and about 10 minutes for delays. The use of cruise/descent speed profile control to determine the time of arrival is then compared with current practice in Figure 25(b), as discussed in Section 3.

(d) Profile selection

Once the scheduler/sequencer has determined the possible optimum sequence of transit times, the definition of the cruise/descent speed profile results directly from the characteristics of the fuel (or cost)/time relationship. As indicated, the availability of aircraft trajectory and consumption data in PARZOC form greatly facilitates the selection of such profiles.

(e) Limitations

In addition to the limitations resulting from the range of operationally acceptable speeds and the position shifts in the sequencing process already mentioned, other constraints arise from workload and communication considerations. As a result, it is advisable to limit the ground-based control directives to a minimum : one for the cruise, one for the descent, one for holding (if necessary), and of course those relating to conflict avoidance, whenever applicable.

A summary of the ZOC concept principles is given in Table 5.

(*) Figures 25 (a) and (b) are given on page 32.

ZOC OBJECTIVES

. Enhance safety
. Controller workload reduction
. Maximum use of available capacity
. Minimum flight cost (transit fuel/time)

SAFETY CONSTRAINT

Separation at runway : separation matrix
Separation along route : . horizontal plane : 5 nm
. vertical plane : $\leq$ FL 290 : 1000 ft
$>$ FL 290 : 2000 ft

ECONOMY CRITERION

Minimize : $\sum_{a} (f.z + p.t)$ a : aircraft in system

CONTROL VARIABLES

Transit time control

speed profile : . cruise and descent components (allowable operational range)
. if insufficient, then :

holding : $\leq$ 1 min hold : path stretching
$>$ 1 min hold : high altitude circuits

Landing order

reference : first come, first served at runway on basis of preferential profiles (fcfsrw)

max position shift : 2 wrt fcfsrw reference

COMMUNICATION CONSTRAINT

FMS equiped a/c : arrival conditions (time, altitude, speed) at :
. characteristic points
. assembly point

FMS non-equiped a/c : . cruise speed profile (frozen at entry)
. descent speed profile (frozen 1 minute before transition to descent)

PRINCIPLES OF THE ZONE OF CONVERGENCE CONCEPT

Table 5

5.4. Concept assessment

5.4.1. Off-line validation

Preliminary results based on a schematic zone and computer-generated traffic samples were reported in 1980 (Ref.13). Since then, the concept has been applied to actual geographical and traffic situations. A preliminary analysis using the branch-and-bound optimising technique (Ref. 21) was made for traffic inbound to London-Heathrow (Ref. 22). It was followed by a detailed investigation using actual flight and traffic data representing flight operations at medium-and high-density terminals in Europe (Refs. 23 and 24). This confirmed the fact noted in Section 4 : an extremely simple organisation of the traffic ensuring maximum use of available runway capacity, combined with the control of cruise/descent speed profiles would bring 80 to 90 % of the potential benefits.

5.4.2. Ground/air liaison

Accordingly, special attention is given to the ground/air liaison required to transfer the directives to the cockpit. To this effect, a procedure is defined and tested in real time. This will be presented further, in Section 6.

5.4.3. ATC Real time simulation

Moreover, the essential principles of the concept are currently being tested at the EUROCONTROL Experimental Centre, using the Centre's real time simulation facilities. Some aspects of this exercise will be presented at the International Symposium on "ATC Contribution to Fuel Economy" (Ref.3): a complete report on the simulation is expected in Spring 1983. At this stage, some pertinent features of the exercise can nevertheless be reported.

(a) Objective of the simulation

The objective of this real time simulation is to expose the ZOC concept to an actual air traffic control environment. As this was the first simulation exercise of this nature, some simplifications have been introduced.

(b) Simulation environment

. Airspace structure

The simulation area covered the whole of Belgium. During the various exercises only traffic inbound to Brussels National airport was considered. The airspace was divided into two areas, West and East, each controlled from an area control position. The final part of the flight was controlled from an approach control position.

. Hardware tools

Beside the normal SDD's and EDD's available at all positions, the approach controller was able to make use of an additional display referred to as the "Landing Interval Display" (LID) for visualising the sequence of expected landings.

. Exercise implementation

The standard simulation and communications facilities of the Experimental Centre were used. These were complemented by a mini computer dedicated to the calculation of aircraft trajectories, associated flight cost (time and fuel components) and the optimised sequencing and scheduling of the inbound traffic.

(c) Organisation of the simulation

Each traffic sample was processed in three different modes :

A. Current-day practice without further assistance.

B. The controller is assisted by the results from the optimised sequencer/scheduler defining for each aircraft the transit speed profile and TOD time.

C. Automatic mode during which the directives of the sequencer/scheduler are automatically applied by the aircraft.

(d) Interim results

At the time of writing, the exercise is still in progress, and the final conclusions of the simulation are not yet available. However, from debriefings conducted with the ATC controllers the following general comments were noted.

The availability of optimised transit speed profile and top-of-descent location was highly appreciated by all participating controllers. No one disputed the basic ZOC concept. In particular, it was observed that, although the traffic samples were not heavily loaded, the controller workload in mode B was considerably less than in mode A as practised today.

Besides the expected comments relating to the simplifications accepted for the initial exercise, most comments referred to possible improvements of the zone definition, the formats and contents of the messages

provided by the system and other particular aspects such as the lay-out of the "landing interval display".

5.5. Potential benefits

In view of the criterion imposed, the ZOC concept should make it possible to achieve the following :

(a) minimum total cost for all flights in the zone;
(b) maximum use of available landing capacity, especially when traffic is at saturation level;
(c) considerable reduction of potential conflicts in the zone covered, both enroute and in the terminal area.

The terms of the criterion could easily be adapted to particular policy requirements and thus encourage low-consumption aircraft or even penalise carriers whose consumption is excessive.

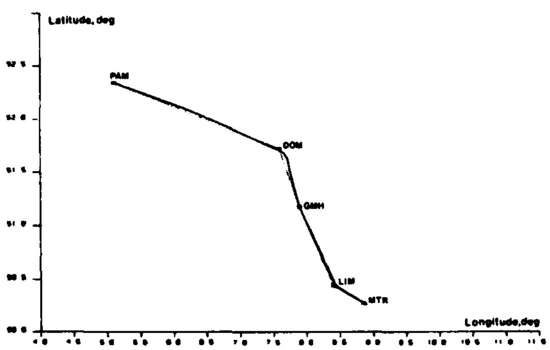
6. THE DYNAMIC CONTROL OF INBOUND FLIGHTS

6.1. Ground-air coordinated trajectory control procedure

6.1.1. Definition

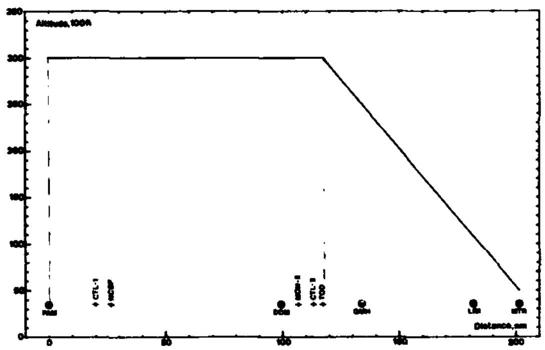
The definition and assessment of a procedure for the control of the trajectory, given a landing time gate, constitutes an essential step for the efficient control of inbound traffic.

For a general flight configuration as illustrated in Figure 26, a number of characteristic points are defined.



Definition of the route

Figure 26



Sequence of characteristic points

Figure 27

They are represented as indicated in Figure 27. Besides the usual waypoints, these include for monitoring (MON) and control (CTL) purposes :

- MON-1 : entry point into actual control zone,
- CTL-1 : Where to initiate, if applicable, transition from entry cruise speed (normally preferential profile) to zone cruise-speed (if requested to adjust time of arrival);
- NCSP : where new cruise speed is expected to be reached;
- MON-2 : monitoring of aircraft progress; information to be used for trajectory correction purposes;
- CTL-2 : initiation of transition between cruise and descent;
- TOD : initiation of descent phase;
- MON-3 : arrival over assembly point.

The procedure will be outlined in Section 6.1.2, while the ground-air messages involved are given in Section 6.3.

To assess such a procedure, a series of experiments were conducted in real time using airlines' flight simulators and qualified officers in particular at Lufthansa using the Boeing B-737 and Airbus A-300 (Frankfurt) and at SABENA using the McDonnell Douglas DC-10 (Brussels). These experiments are reported in References 10 and 11. The ground-based air traffic control function was simulated using a small portable micro processor. Various air-ground communications environments could be envisaged, either present voice communications (R/T), or automated transfer of digitized information (data link) using printed messages, or even a combination of both.

6.1.2. Contents

(a) Provision is made to control the transit through changes in speed profile at two distinct points, marked CTL-1 ad CTL-2.

(b) Alteration of cruise speed can be initiated if necessary at CTL-1, located 10 to 20 nm from entry

in the direction of the flight. In the case considered, this point was located at 20 nm from Pampus.

(c) The transition between cruise conditions and descent was initiated at CTL-2. Accordingly, the position of this particular point varies in space, depending on the descent speed value and the difference between cruise and descent speeds.

(d) The instructions were sent to the pilot usually thirty to sixty seconds before arrival at the control points.

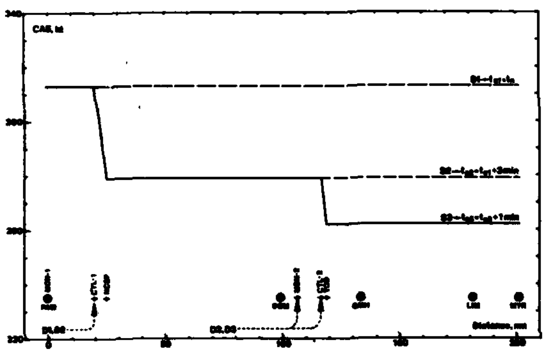
(e) The directives included :

. the position of the control point (CTL-1 or CTL-2) which was given to the pilot in terms of a DME distance to an appropriate beacon;

. the value of the speed (expressed in Mach number of CAS) for the component concerned, namely cruise for CTL-1 and descent for CTL-2.

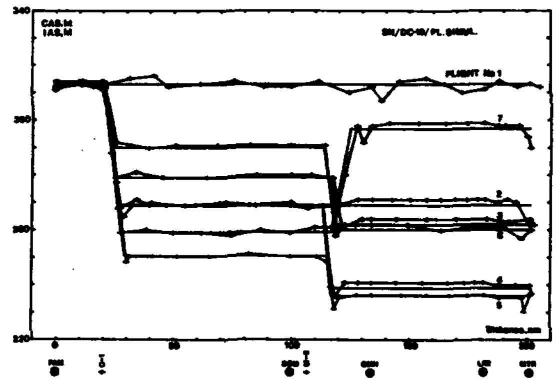
(f) The top of descent (TOD) loction which resulted from the above.

(g) The aim was to reach the assembly point, in this case Metro (MTR), at an altitude of 5,000 feet. For flight evaluation purposes, if the altitude over Metro exceeded this value, the pilot would be requested to maintain speed and aircraft configuration and proceed until the aircraft had descended to 5,000 feet. However, if the aircraft descended to 5,000 feet before Metro , the pilot was to proceed to Metro at a constant altitude of 5,000 feet while maintaining the scheduled en-route descent speed.



Speed selection for the control of the arrival time

Figure 28



Range of speed profiles covered

Figure 29

6.2. Plans and plan alterations

When the aircraft enters the control zone, the arrival time and speed at the assembly point MTR are defined by the scheduler/sequencer algorithms.

A plan or prediction of the flight progress is then made, covering the nominal speed components and, for the waypoints, monitor and control positions, the time, altitude, distance from entry, distance to the assembly point Metro (MTR) and distance to destination.

Plan alterations were basically envisaged to update or amend the arrival time over the assembly point. Essentially, such amendments would result either from a correction of the trajectory, following observations (surveillance) at MON-2 or from a change in the required arrival time at the assembly point due to a possible rearrangement of the scheduling of the particular flight concerned.

With the micro processor used, the time needed to calculate and print the complete initial clearance was about twenty seconds ; generation and printing of the alteration directives took some five seconds.

6.3. Ground-air communication

With respect to the control of the trajectory, three messages were sent from the simulated ground-based control to the aircraft. Their contents in terms of information is summarised hereafter :

(a) Message 1 constitutes a confirmation of the entry clearance (route, altitude, cruise speed). It is sent to aircraft at entry into the zone.

(b) Message 2, whenever applicable, is sent to aircraft one minute before CTL-1. It defines the alteration of the cruise speed. It contains the new cruise speed, location of initiation of manoeuvres expressed in DME-distance from DOM.

(c) Message 3, whenever applicable, is sent to aircraft one minute before CTL-2. It constitutes a notification of the descent speed component, and c ntains the descent speed and the location of initiation of manoeuvre (DME distance from FFM).

Despite the modest computing facilities available, the nature of the procedure proposed makes it possible to envisage two modes of communications, namely voice and data link. This aspect should be the subject of specific investigations and will not be discussed further in this paper.

6.4. Illustration of the control procedure using the SABENA DC-10 flight simulator

Figure 28 illustrates the definition of the successive cruise/descent speed profiles selected to reach the assembly point considered (in this case Metro, MTR, at 5,000 feet) at the requested time. The cruise/descent speed profile used will be represented by the sequence

S = CR1/CR2/DE

where CR1, CR2 and DE are the speed indications (either CAS, kt, or Mach number) for the phase MON-1 to CTL-1, NCSP-1 to CTL-2, TOD to the assembly point, here Metro.

Using the pilot's preferred profile or nominal profile (SN), namely

S1 = SN = 313/313/313 (CAS, kt)

the time of arrival over Metro would have been the nominal time (TN) that is to say 26:48 (min:sec) after entry, in this case over Pampus.

If, in view of the traffic situation at the destination airport, in this case Frankfurt, the arrival is to be delayed by M1, say 3, minutes, the corresponding speed profile becomes

S2 = 313/CR2/DE2 (CAS, kt) or S2=313/279/279 (CAS, kt)

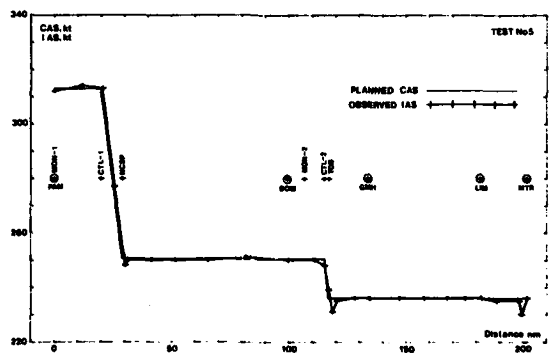
i.e. a smooth cruise-to-descent speed transition for which CR2 = DE2. The relevant directive (D2) contains the value of the new cruise speed, CR2, and the position (DME distance) of CTL-1 at which the change of speed is to be initiated. If the time of arrival, T2 is maintained, then the second part of directive D2, namely the descent speed DE2 and the position of CTL-2 (DME-distance) where, in this case the descent is to be initiated, is passed to the pilot, for example one minute before reaching CTL-2.

If however, in view of the situation, air traffic control required a modification of the time of arrival as it would result from S2, for instance M2 minutes later (one minute in the example) a new descent profile could be suggested

S3 = 313/CR2/DE3 (CAS, kt) or S3=313/279/262 (CAS, kt)

The relevant directive (D3) contains the value of the new descent speed (DE3) and the position of CTL-2 at which the change should be initiated. It is sent to the aircraft one minute before CTL-2.

Figure 28, which illustrates such a procedure, corresponds to a particular flight in the exercise, conducted on the SABENA DC-10 simulator.



Observed IAS versus planned CAS

Figure 30

6.5. Range of operation covered

6.5.1. Range of speed profiles

In order to test the procedure proposed, some fifteen flights were made. These included accelerations and decelerations, which may in some cases have affected the passengers' comfort, but were in fact selected to cover an as wide as posible range of operating conditions.

To give an idea of the range of speeds covered, a summary of the profiles used is presented in Figure 29 for the flights conducted on the SABENA DC-10 simulator. For the sake of simplicity, the diagram shows only the ultimate profile, namely S3.

This figure also constitutes an overall summary of the implementation of, and adherence to, given

cruise/descent profiles. The crosses indicate observation data. As can be seen, the observed and requested profiles agree extremely well, although, as mentioned below, various modes of acceleration were used.

6.5.2. Control range of the arrival time

From the operational speed range of the aircraft concerned and the airline's recommended profile, the available control range of the time of arrival is readily derived. This was discussed in Section 2 and 3 where Figure 10 corresponded to flights such as these, namely flights conducted using the DC-10 aircraft from Pampus to Metro; the point marked "p" on the diagram corresponding to the preferential profile.

6.5.3. Aircraft operation

No request was made for particular navigation equipment as the aircraft was operated in accordance with everyday practice. The speed-hold mode of the autopilot, available in the DC 10-30, was used at the discretion of the pilot. For acceleration or deceleration, the thrust setting was modified either manually or by using the autothrottle. This in fact constituted a parameter in these experiments. The descent phase to Metro was flown at "flight-idle" power setting.

6.6. Dynamic control of trajectories

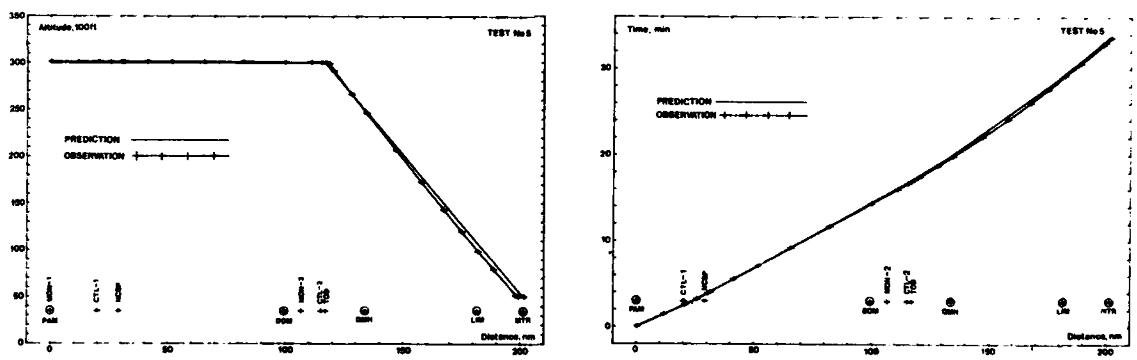
The results obtained are summarised hereafter for a typical fight of the DC-10.

In Figure 26, the route flown is compared with the route initialy planned. As shown on the map, the change of direction is initiated when passing the relevant apex. This practice was used throughout the exercise; although some reduction of length might result from the use of a circular connection initiated before the apex. This could easily be incorporated in the procedure whenever required.

Figure 29 shows how the pilot follows the speed profile directives, in particular :

(a) change of cruise speed;
(b) change from cruise to descent profile;
(c) adherence to planned speed throughout the flight.

The results obtained for Test number 5, for which the speed was reduced in two steps from the preferential value to almost the minimum allowable, are shown separately in Figure 30.



(a) (b)

Altitude (a) and progress (b) as planned and observed along the route

Figure 31

Figure 31(a) compares the altitude as planned and observed along the complete route. When the results were analysed the quality of the arrival time prediction was found to be closely related to the top-of-descent position accuracy. In the case illustrated, the aircraft arrives over Metro within 300 feet of the expected value.

Figure 31(b) shows the progress of the flight along the route. It compares the time at which the aircraft is expected with the time at which it actually passes any given point along the route.

6.7. Control accuracy

From the series of experiments conducted to date, it would appear that the proposed procedure is suitable to control the time of arrival of the aircraft at the assembly point with a high degree of accuracy.

It is worth noting that these results were obtained without any trajectory update, in a standard, no wind, atmosphere. Nevertheless, the overall analysis shows that when all the inaccuracies inherent in the

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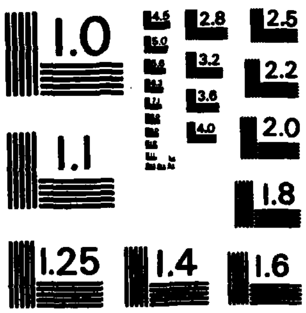

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ground and air coordinated control system, including human factors, are taken into account, the maximum discrepancy in arrival time after a 200-nm flight distance remains within 26 seconds.

6.8. Impact on consumption and cost

The use of such a procedure would yield the benefits estimated in Section 3. The Figures 25(a) and (b) given as illustrations previously correspond to the flights conducted from Pampus to Metro on the DC-10 aircraft. Figure 25(a) shows the increase in consumption with the time of transit, that is to say with the delay imposed by Air Traffic Control as a resuslt of the traffic situation in Frankfort. The diagram gives the transit consumption for four control techniques, two being retained for comparison purposes, the recommended cruise/descent speed profile control and the hold at cruise altitude.

Some alterations of the preferential times of arrival being probably unavoidable, at least for some period of time, the use of cruise/descent speed control would bring benefits as illustrated in Figure 25(b) : savings of the order of 500 to 1000 kg of fuel for excess transit times ranging from 5 to 10 minutes. This would correspond in fact to a reduction of 63 per cent of the extra cost associated with such alterations.

6.9. On-line experiments

Preliminary on-line experiments have been conducted during actual regular scheduled flights in co-operation with British Airways and the Air Traffic Control Authorities of Belgium (RVA/RLW) and of the United Kingdom (CAA/LATCC).

Aircraft (Trident 3B and BAC 1-11) inbound to Brussels-National, coming from Birmingham, London and Zurich were given precise directives as where to initiate the descent. The relevant decision being taken some 80 nm from the runway.

The meteorological information used was the one available at the Control Centre in Brussels. The mass of the aircraft over Dover was passed to the ground using the ATC voice channel. The Integrated Flight Prediction System (IFLIPS) was used for the profile definition and prediction.

For a series of some 20 flights, the maximum discrepancy observed at landing was less than 30 seconds. The accuracy of prediction at the 7000-ft point being appreciably better. These results were obtained without update or correction over a 80-nm extent. An illustration of the results obtained is given for a typical flight in Figure 32.

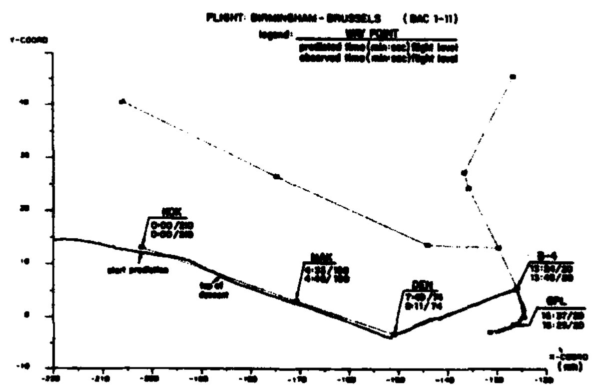

Illustration of actual on-line prediction
including
TOD definition by ATC

Figure 32

7. CONCLUSIONS

In an extended area surrounding and including a main terminal, appropriate control of the flight could appreciably reduce the overall air transport cost. For inbound traffic only, potential reductions could be of the order of 10 to 25 % of the present fuel burn, the actual amount depending on local and seasonal traffic conditions.

Cruise/descent speed control is an essential part of any system aimed at increasing the efficiency of control in such areas. It will contribute to the reduction of overall delays and, especially for given transit time extensions, to appreciable savings in cost.

One possible duly coordinated ground/air control procedure is proposed. It is being tested using aircraft flight simulators operated by airline pilots. The results obtained constitute a successful although preliminary assessment of the feasibility, accuracy and implications of a 4-dimensional trajectory control executed with commercial aircraft currently in operation.

Further, limited experiments of active control of aircraft have been conducted during actual regular scheduled flights, the relevant control directives being transmitted to the pilot by the ATC controller. Although limited to some eight flights inbound to Brussels Airport, these experiments confirmed the operational compatibility of the control procedures proposed.

The concept of a Zone of Convergence (ZOC) as outlined briefly in this paper aims at using the available aircraft trajectory control range to control inbound flights in accordance with an overall economy criterion.

An optimum sequencing/scheduling technique would ensure maximum use of the available runway capacity. At the same time, it reduces the number of conflicts in the resulting traffic, which in principle, for given separation standards, enhances safety.

The basic principles of the Zone of Convergence concept are being tested in an operational environment. The effectiveness of the processes under consideration, as an aid to the ATC controllers is being assessed in real time using the simulation facilities available at the EUROCONTROL Experimental Centre. The results obtained to date are most encouraging and certainly serve to confirm the potential contribution of ATC to the economy of air transport.

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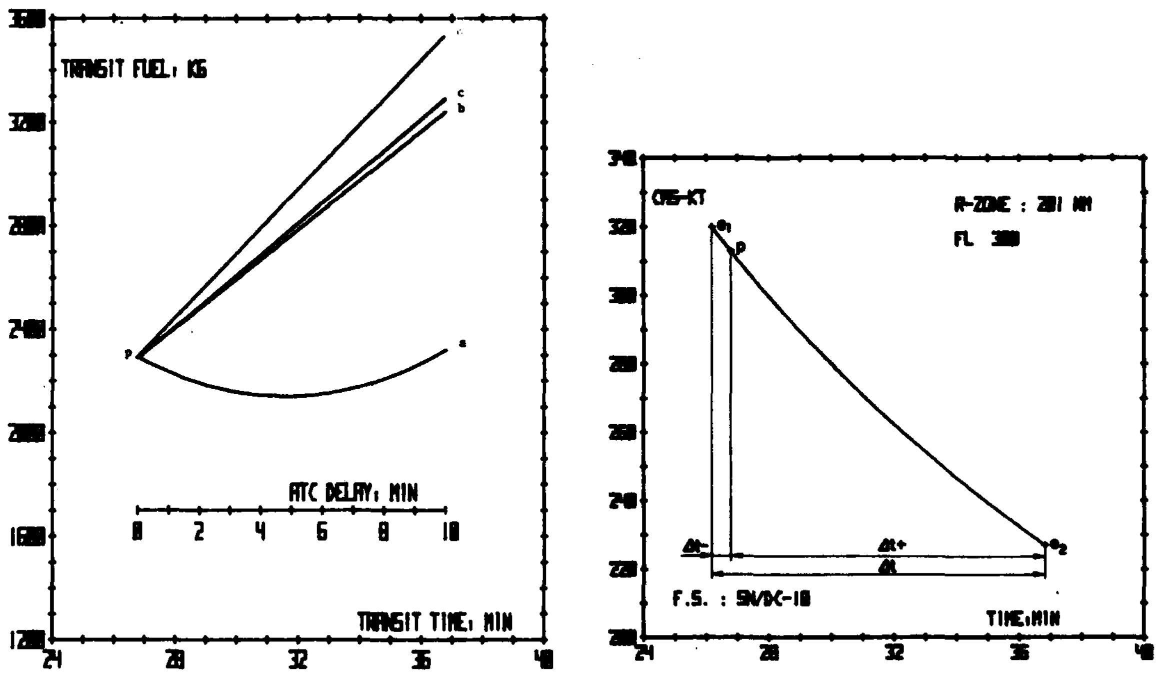

a. Control of cruise-descent speed
b, c. Holding at cruise and low altitude, respectively
d. Path stretching at cruise conditions

(a) Consumption/time relationship

(b) Range of arrival control

Control range and benefits resulting from cruise/descent speed control

Figure 25

DISCLAIMER

The views expressed in this paper are those of the authors. They do not necessarily reflect the policy of the EUROCONTROL Agency.

INVESTIGATIONS ON FOUR-DIMENSIONAL GUIDANCE IN THE TMA

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SUMMARY

The four-dimensional (4D) guidance of aircraft in the TMA allows for precise control of the minimum separation and thus efficient use of the available approach capacity of the respective airport. At the DFVLR Institute of Flight Guidance at Braunschweig a concept for the 4D guidance of transport aircraft has been developed and a corresponding control mode has been integrated in an automatic flight control system for transport aircraft. This was tested on the DFVLR's HFB 320 test aircraft. The 4D mode is based on usual radar vector guidance technique of air traffic control and, therefore, is characterized by a succession of flight sections with constant values for indicated airspeed, heading and descent rate. The time-of-arrival is controlled by altering the path via a delay fan. The algorithm for the calculation of the commanded 4D flightpath takes into account suitable wind models updated by actual wind data. In the paper the 4D mode is described and first flight test results are discussed.

SYMBOLS AND ABBREVIATIONS

a,b	coefficients for the approximation of the true airspeed
a_i, b_i, c_i, d_i	coefficients of a cubic spline function
AFCS	Automatic Flight Control System
ATC	Air Traffic Control
CP_i	intercept waypoint on the centerline
CPI, CPA	boundary waypoints on the centerline
CPU	central processor unit
d	differentiation
FCC	Flight Control Computer
FL	Flight Level
FMS	Flight Management System
FP	fan waypoint
g	gravity constant
GT	waypoint at the merge gate
h	altitude
l_v	drift angle
p	exponent of the physical wind model
q	factor of the physical wind model
r_1, r_2	coefficients of a quadratic function
STAR	Standard Arrival Route
t	variable time parameter
T	time period
TCC	Thrust Control Computer
TMA	Terminal Maneuvering Area
TOA	Time-of-Arrival
u_g	ground speed
UP_i	update waypoint
v_{IAS}	indicated airspeed
v_{TAS}	true airspeed
vw	wind velocity
x, y	components of the flightpath
α_W	wind direction
Δ	difference
θ	pitch angle
σ	standard deviation
ϕ	bank angle
χ	course
ψ	heading
$\dot{\psi}$	turn rate

SUBSCRIPTS

E	east components
N	north components
o	reference value

1. INTRODUCTION

The increase in air traffic during the last decades and the restrictions with regard to noise went along with a considerable increase in flying time. Long and time-consuming take-off and approach procedures and a limited airspeed below FL 100 became necessary. Every day the limit of airport approach capacity is reached or exceeded several times at large international airports such as Frankfurt. Therefore congestion and uneconomic delays occur [1, 2].

Nominally the aircraft is supposed to follow the predefined standard arrival route (STAR) and the corresponding altitudes published for the respective airport [3]. During traffic peaks, however, the approach flightpath deviates from this standard arrival route and the pilot then receives individual instructions via VHF COM from air traffic control. The aircraft motion is displayed on the controller's radar screen and on the basis of the radar picture the controller allocates courses and speeds (radar vectors) as well as altitudes to the individual aircraft, in order to guide it to the centerline at a suitable separation between aircraft.

There is a minimum separation margin between successive aircraft which must not be violated during final approach. The separation margins ought to be adjusted at the merge gate at the latest, i.e. on the extended runway centerline shortly before the glidepath is intercepted. For safety reasons the controller has to keep a reserve in separation taking into account possible deviations due to:

- delays in the transmission and execution of VHF COM advisories
- deviations from the planned flightpath
- inprecise knowledge of wind conditions within the TMA.

The air traffic controllers can be supported in their difficult task by increased use of digital computers. On the one hand computers can be applied for planning tasks on the ground and on the other hand airborne computers can guide and control the individual aircraft precisely in space and time. This leads to an automated 4D terminal area guidance system which can offer several advantages as for example:
- the maximum use of the approach capacity of the respective airport by means of precise control of minimum separation margins,
- a reduction of work load for pilots and controllers and
- a general increase in air traffic efficiency.

This paper describes a concept for such a system which is developed by the DFVLR Institute of Flight Guidance at Braunschweig and which was flight tested this year.

2. SOME CONCEPTUAL FEATURES AND ASSUMPTIONS

It is assumed that future ground based ATC systems will provide an automated scheduling and sequencing of arrivals especially during peak periods by an early, integrated planning procedure, such as COMPAS (Computer Orientated Metering Planning and Approach Sequencing) proposed by DFVLR, using updated flight plan and flight progress data and considering a number of constraints [4]. All scheduling and sequencing calculations are performed with reference to the merge gate, but all control actions to establish the desired timely ($\pm$ 30 seconds) and orderly delivery to the "metering fixes" have to be carried out on the adjecent enroute sectors. Therefore holding procedures within the TMA below FL 100 are reduced to a minimum. The final spacing function ist performed in combination with the 4D guidance system. During the TMA flight spanning from the metering fix to the merge gate the TOA error should be reduced to 5 seconds (2σ-value). At the merge gate the aircraft is supposed to have assumed a given state in speed and altitude.

2.1 Share of sub tasks between the ground based and the airborne systems

When entering the TMA the aircraft has reached a flight level below or equal FL 100 and an indicated airspeed of less than 250 kts. The ground based ATC planning algorithm computes a conflict-free flightpath from the TMA entering point (metering fix) to the merge gate, taking into account individual requests for fuel-saving or cost-saving speed and altitude profiles. For most of the civil transport aircraft with their relatively similar aerodynamic behaviour the aircraft should maintain their altitude and speed as long as possible close to FL 100 and to the maximum permitted speed of 250 kts, respectively.

On the basis of the computed flightpath the individual aircraft receives corresponding guidance commands for indicated airspeed, altitude and lateral control. The data flow between ground and airborne systems is shown in Fig. 1. In accordance with conventional procedures, aircraft without a FMS obtain conventional radar vector and altitude information from the ground by VHF COM, however all these informations are derived from the ATC planning algorithm. It is part of the pilot's responsibility to follow these commands as accurately as possible for instance by use of automatic systems like FCC/TCC or manual control.

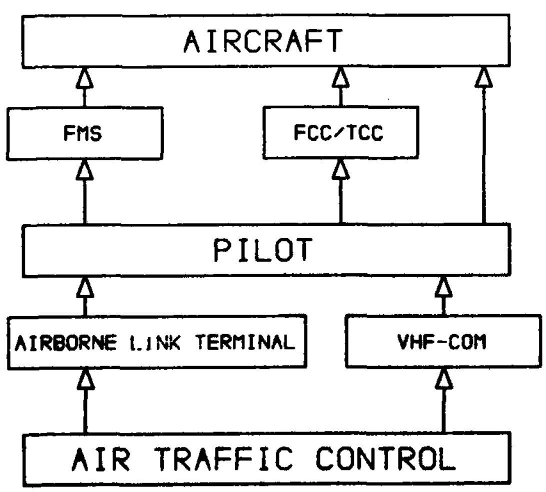


Figure 1: Data flow between the ground based system and the airborne system

Those aircraft which are equipped with a FMS can autonomously follow 4D commands of the ground planning. They obtain a coded information from the ground indicating the constraints for the horizontal flightpath, the TOA at the gate, the altitude and the speed to be maintained during intermediate approach and at the merge gate. In addition, information is given about the wind in the TMA.

The FCC/TCC guides the aircraft on this path and controls the altitude and airspeed. The tracking of the lateral flight path is based on a control mode by which lateral deviations can be automatically brought to zero and changes for a new radial at a 4D waypoint can be carried out by a turn with constant bank angle. In addition, the TOA error is monitored and the wind model is updated by means of wind measurements obtained from aircraft sensors. If the expected TOA error exceeds certain limits a correction of the original flightpath becomes necessary.

Knowledge of the wind is of great importance for the planning computations if precise TOA control is desired. For this reason it is assumed that the ground based computer processes general meteorological data as well as wind data which are measured by the aircraft sensor system and transmitted to the ground by data-link. A 3D map of the wind profiles in the TMA can be produced on the ground (windmapping) from which magnitude and direction of the wind can be derived for each individual approach path.

At present ATC guidance commands are still transmitted by VHF COM. However, in future it is planned to use a data-link with an appropriate airborne receiver (airborne link terminal), equipped with a data display, so that these guidance commands can directly be transfered to the aircraft and then be fed into the FMS after acknowledgment by the pilot.

2.2 The principle of time-of-arrival control

TOA control is achieved basically by stretching or shortening the length of the flightpath. It compensates for deviations, for instance those resulting from discrepancies between actual wind and modelled wind during approach. For this purpose the intercept waypoint CP can be moved along the centerline (Fig. 2). All possible flightpaths form a fan area, which is limited by two boundary waypoints CPI and CPA. In case the fan does not provide sufficient delay for TOA control because of extraordinary deviations from the command in TOA an appropriate number of holdings must be performed. The TOA error is continously computed during the approach and if it exceeds previously defined limits an update computation is started resulting in a new flightpath. The initial waypoint UP_1 (Fig. 2) of the new flightpath corresponds to the actual position of the aircraft and a new intercept point on the centerline is determined.

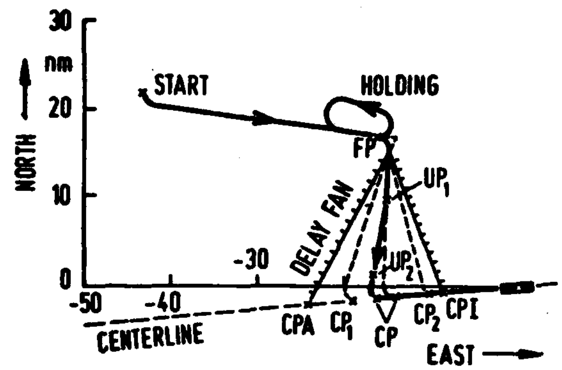


Figure 2: Horizontal flightpath

Once the aircraft has reached the waypoint UP_2 situated close to the centerline path corrections are no longer possible. At this stage speed control is applied, but only by shifting the point where the speed reduction to final approach speed is started.

Fig. 3 represents the switching function for the flightpath update a so-called time error window as a function of flight time. The acceptable TOA error is 20 seconds when starting the 4D mode. In any case, flightpath computation take place at the fan waypoint FP and at waypoint UP_2 which is located approximately one minute before the centerline is intercepted. The path correction is entered by setting the switching function to zero. Between both waypoints the time error window linearly decreases from 20 seconds to 5 seconds.

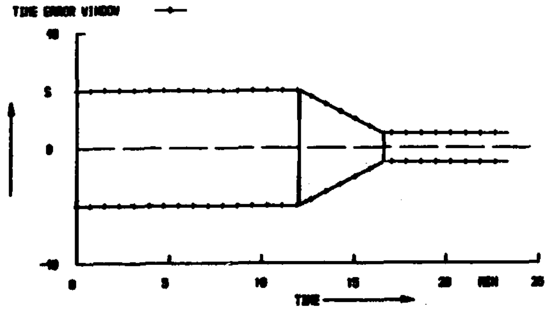


Figure 3: Time error window for flightpath update

2.3 Selection of the guidance commands

The selection of suitable guidance commands is of great importance for operational response and for the integration with a partly or fully automatic flight control system. The commands to be transmitted to the aircraft - in particular in case of VHF COM transmissions - should correspond to the standardized guidance commands for current 3D flightpath control systems. Thus altitude or vertical speed, indicated airspeed and heading have to be used as command parameters.

The commanded 4D flightpath consists of straight-line and circular-arc segments. For the circular-arc segments a constant bank angle is commanded, i.e. the geometry of these path segments with respect to the ground is affected by the wind. The straight-line segments simply represent radials to flightpath waypoints. All this does not create any compatibility problem with regard to current autopilot systems.

When the 4D approach is initiated the aircraft assumes the v_{IAS} command assigned to it by ATC at that time. Then, this command is executed. The reduction in speed is performed at a constant deceleration rate. In level flight a higher deceleration rate is applied than during descent. If a FMS is available and the deceleration profile can possibly be determined for an idle approach, this can be taken into account in the 4D flightpath algorithms.

Fig. 4 shows a plot of a typical 4D approach command profile. At the beginning of the approach the aircraft decelerates to an intermediate speed and at the same time descends to an intermediate flight level. After about 3 minutes a new flight level, for example, FL 60, is commanded by the ATC controller. Altitude and speed, assigned for the merge gate are already achieved during the intercept of the centerline.

2.4 Wind modelling

One essential task in flight-testing the 4D mode is to examine different wind models with regard to their suitability for predicting wind profiles for the altitude range associated to the 4D approach. For this purpose different wind models and update algorithms are used.

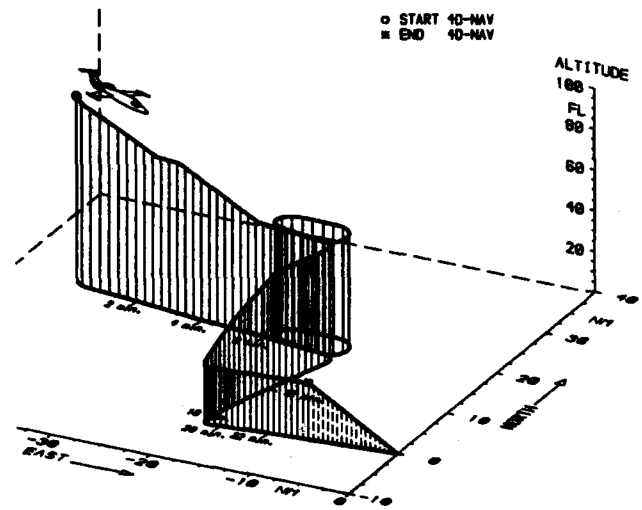


Figure 4: Typical simulated 4D approach

Using common airborne sensors of a transport aircraft a measurement of the wind at the actual aircraft position in terms of magnitude and direction is taken continuously. On the basis of this measurement wind data are entered into the computation of the 4D flightpath as a function of altitude. Additional wind measurements available on the ground or onboard of aircraft flying ahead are of great importance in order to update the wind models. The following types of wind modelling are considered with regard to how the wind measurement data are processed:

- interpolation of a reference wind measurement at runway level or at certain altitude and wind data measured by airborne sensors. The interpolation algorithm corresponds to analytical relationships
- interpolation of several wind measurements at different altitudes by mathematical functions
- short-time wind prediction based only on airborne measurements.

3. THE DETERMINATION OF THE 4D FLIGHTPATH

3.1 The horizontal flightpath

Only iterative and fast-converging computation procedures are suitable for calculating the horizontal flightpath because this task has to be executed real time during flight. Fig. 5 illustrates the basic geometric problem which has to be solved.

The following equations apply for the circular-arc path segments affected by the wind:

$$x = R \cdot [\sin(\Delta\psi - l_v) + \sin(l_v)] + \int_0^t vw_E \cdot dt \qquad (1)$$

$$y = R \cdot [\cos(l_v) + \cos(\Delta\psi - l_v)] + \int_0^t vw_N \cdot dt \qquad (2)$$

$$R = v^2_{TAS}/(g \cdot \tan\phi) \qquad (3)$$

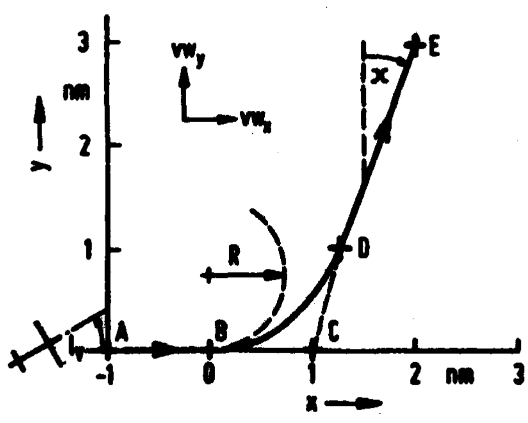


Figure 5: Connection of straight-line and circular-arc segments

The basic task to be carried out first is to link a radial from the 4D waypoint E to the bent path segment by means of putting up a tangent. The following equations apply at the point D where the straight-line segment begins and the bent segment ends:

$$m_1 = (dy/d\chi) \,/\, (dx/d\chi) \qquad (4)$$

$$m_2 = (y_E - y_D) \,/\, (x_E - x_D) \qquad (5)$$

i.e. the direction m_2 of the straight-line segment from D to E must be equal to the direction m_1 of the tangent at the point D.

If the derivatives of equations (1, 2) are inserted into equation (4), the result is a non-linear, transcendent equation which can be solved numerically by using an iterative procedure. Since the initial value $\Delta\psi_o$ of the iteration can be precisely determined because of the simple geometry of the flightpath, 2 to 3 iterations are sufficient to determine the course angle to the waypoint D, i.e. with an accuracy of about 0.01 degrees.

If two bent segments have to be linked by a common tangent it is possible to transfer this task to the basic problem described above. Again only 3 iterations are sufficient to solve this kind of problem. The same procedure is used to calculate a holding pattern or to determine a flightpath update. These procedures characterized by a particularly fast convergence were proposed in [8,9].

3.2 The 4D flightpath

Based on the horizontal flightpath, the corresponding TOA at the merge gate is calculated with reference to the altitude and the speed profile. For this purpose the known profile of the v_{IAS} is used to calculate the v_{TAS} using the equation (6). The influence of air density as a function of altitude is covered by an approximation:

$$v_{TAS} = v_{IAS} \cdot [1 + a \cdot h + b \cdot h^2] \tag{6}$$

The ground speed can approximately be calculated by use of the track angle χ, v_{TAS} and the wind described by the wind model. According to the wind triangle shown in Fig. 6 Eq. (7) applies:

$$u_g = v_{TAS} - 0.5 \cdot vw^2 \cdot \sin(\chi - \alpha_W)/v_{TAS} + vw \cdot \cos(\chi - \alpha_W) \tag{7}$$

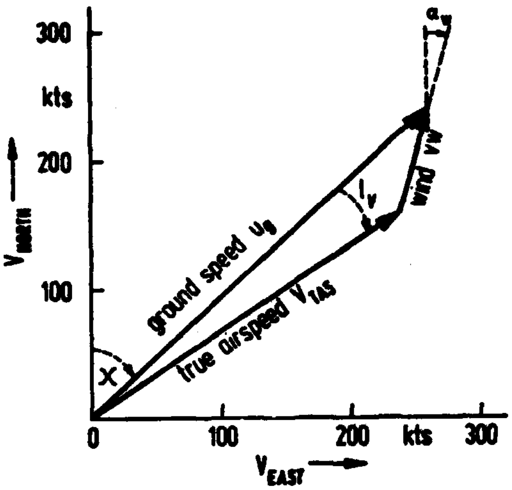


Figure 6: Wind triangle

The calculation of the flight-time elapsed on a leg ΔL requires an integration of the time-dependent ground speed:

$$\Delta T = \int_0^{\Delta L} dL/u_g(t) \cdot dt \tag{8}$$

This cumbersome integration can be avoided by means of a numerical trick. To do this $u_g(t)$ is numerically integrated until the integral reaches the value ΔL. The number of steps required multiplied by the time interval of the integration then gives the desired value ΔT. Relatively large time segments are possible because an interpolation calculation is made after the last step.

If equation (8) is applied for the circular-arc segments too, the value of ΔL would correspond to the length of the bent segment. In order to avoid calculations of great time consumption the turn rate $\dot{\psi}$ and the change of the heading angle $\Delta\psi$ are used instead of u_g and ΔL.

$$\Delta T = \int_0^{\Delta\psi} d\psi/\dot{\psi}(t) = \int_0^{\Delta\psi} d\psi \cdot g \cdot \tan\phi / v_{TAS} \cdot dt \tag{9}$$

The time ΔT again is obtained from the number of steps $\Delta\psi$. Finally, the flight-time for the complete 3D flightpath including the altitude profile is obtained by adding up the flight-times of the individual segments of the flightpath.

The calculation of a 4D flightpath, however, requires the inverse procedure, i.e. the flightpath must be determined for a given TOA at the merge gate. However this direct way includes complicated numerical procedures, and for this reason an iterative method is used again: The TOAs of 2 different flightpaths TOA_1 and TOA_2 are calculated, for example, for the corresponding distances of the intercept waypoints ΔCP_1 and ΔCP_2 from the merge gate. Because of the smooth relation between ΔCP and the desired TOA the desired distance ΔCP can be obtained by linear interpolation in accordance with equation (10):

$$\Delta CP = \Delta CP_1 + (\Delta CP_2 - \Delta CP_1)/(TOA_2 - TOA_1) \cdot TOA \tag{10}$$

At the beginning of the 4D approach the inner and outer boundary waypoints CPI and CPA are selected for ΔCP_1 and ΔCP_2 respectively since the corresponding flightpaths have to be calculated anyway in order to determine the minimum TOA and the number of holdings, if necessary. For the 4D flightpath update to compensate for TOA errors, it is sufficient to locate ΔCP_1 and ΔCP_2 approx. 500 m apart of the actual intercept waypoint in order to receive a high level of accuracy for the interpolation.

3.3 Vertical wind models

During the flight experiments of the 4D mode the wind measurement is carried out by the aircraft's inertial navigation system (INS) and the digital air data computer (DADC).

3.3.1 Interpolation of wind data by analytical relationships

The wind profile can be described by the equation (11):

$$vw = vw_0 \cdot (h/h_0)^p \; ; \; h \geq h_0 \tag{11}$$

The value of p varies between 0 and 1 depending on the air turbulence, the distribution of the static pressure, temperature and humidity of the air, the structure of the earth surface etc. as described in [12]. The value of 0.25 is most commonly used. If the wind is known not only at a reference altitude but also at the actual flight altitude, p can be calculated by re-arranging the equation (11).

A linear interpolation was selected for the wind direction α_W. The factor q can be calculated by two wind measurements, too.

$$\alpha_W = \alpha_{W0} + q \cdot (h-h_0) \quad ; \quad h \geq h_0 \tag{12}$$

In order to check this wind model, data from weather balloons launched by the aeronautical meteorological office at Hannover Airport were used. These data showed adequate correspondence in most cases. The mean value of the deviations was 1 kt with a standard deviation of 4 kts. However, this relatively simple wind model did not give an adequate description of the measured wind profils on days when inversions were observed.

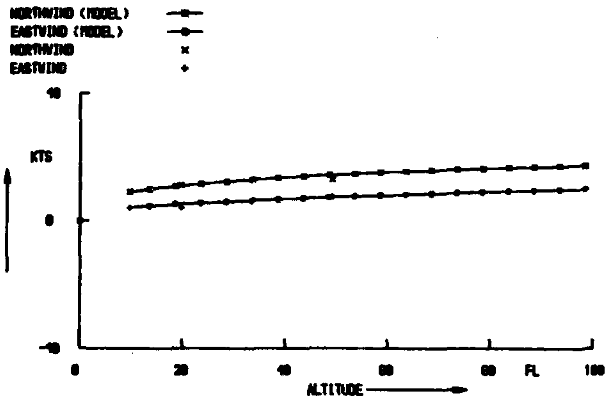


Figure 7: Comparison of measured and modelled wind profiles for the 16th of June, 1979

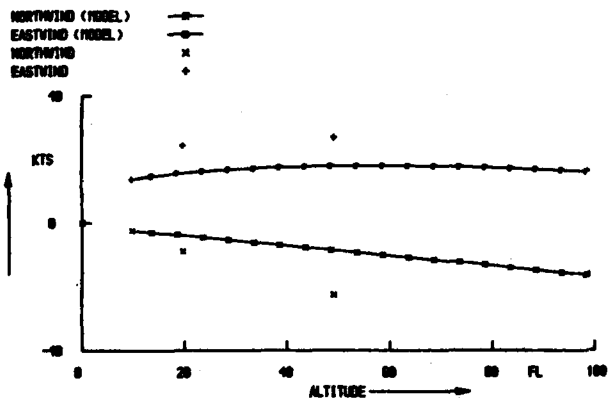


Figure 8: Comparison of measured and modelled wind profiles for the 4th of June, 1979

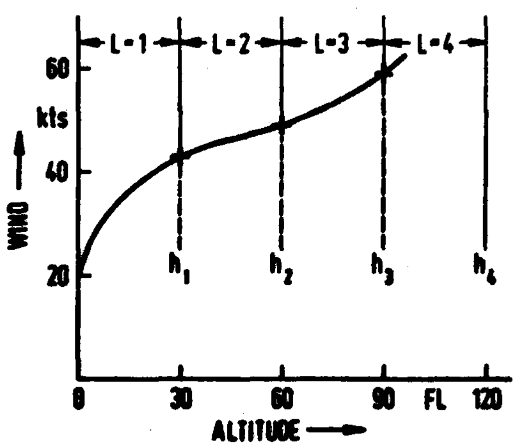


Figure 9: Cubic spline function

Fig. 7 and Fig. 8 compare the measured and modelled wind profiles for 2 different days. The modelled wind profil corresponds to the equations (11) and (12). Whereas in Fig. 7 the wind model gives an adequate description of the measured data, deviations of up to 20 kts occur in Fig. 8. On the 4th of June 1979 the wind magnitude even partly decreases during the climb of the balloon. This clearly demonstrates the problems involved in finding analytical relationships for wind profiles: although from the statistical point of view these relations give an adequate description of the wind profiles on average, possible large deviations on particular days can cause unacceptable TOA errors.

3.3.2 Interpolation of wind data by a spline function

Interpolation of wind data by a spline function is based on a number of wind measurements by ground based sensors and by aircraft flying ahead. In the 4D system presented here a cubic spline function was used (Fig. 9). The full range of altitude during the 4D flight is separated into 4 sections and for each section a total of 4 coefficients are assigned. To ensure a smoothly curved wind profile the calculation of these coefficients for each segment is based on the boundary value of the preceding and the following section. The result is a wind model as described for the east component of the wind by equation (13):

$$vw_E = a_L + b_L(h-h_{L-1}) + c_L(h-h_{L-1})^2 + d_L\,(h-h_{L-1})^3 \;;\; L = 1,\ldots,4 \tag{13}$$

During the test flights the wind data are derived onboard the test aircraft itself, which measures and stores wind data during climb before initializing the 4D mode. After the 4D mode is engaged actual wind data update the coefficients of the spline function.

The advantage of this method lies in the fact that the wind is modelled exactly if it changes slowly. However, this method does require a ground-to-air data-link by which the relevant spline coefficients or certain sets of wind data have to be transmitted.

3.3.3 Short-time prediction of wind profiles

The short-time wind prediction - on the basis of actual wind measurements - takes into account the fact that extremely accurate wind values are needed for the last path correction. In this case, the wind has to be predicted for the time internal of approximately one minute necessary for the last 1000 ft altitude change down to the altitude at the merge gate. All previous wind measurement data of the entire 4D approach flight are taken into account in order to achieve the most accurate wind prediction.

The prediction can be brought about by extrapolation of the wind profile as a function of the deviations observed in comparison with the wind profile used before. Here, an extrapolation polynom is used which is based on the measured wind gradients. For the east component of the wind equations (14), (15) and (16) apply:

$$vw_E = vw_{0E} + r_{1E} \cdot (h-h_0) + r_{2E} \cdot (h-h_0)^2 \quad (14)$$

$$r_{1E} = d(vw_E)/dh \quad ; \quad h = h_0 \quad (15)$$

$$r_{2E} = 0.5 \cdot d^2(vw_E)/dh^2 \; ; \quad h = h_0 \quad (16)$$

4. REALIZATION OF THE EXPERIMENTAL 4D GUIDANCE SYSTEM

4.1 The flight control system

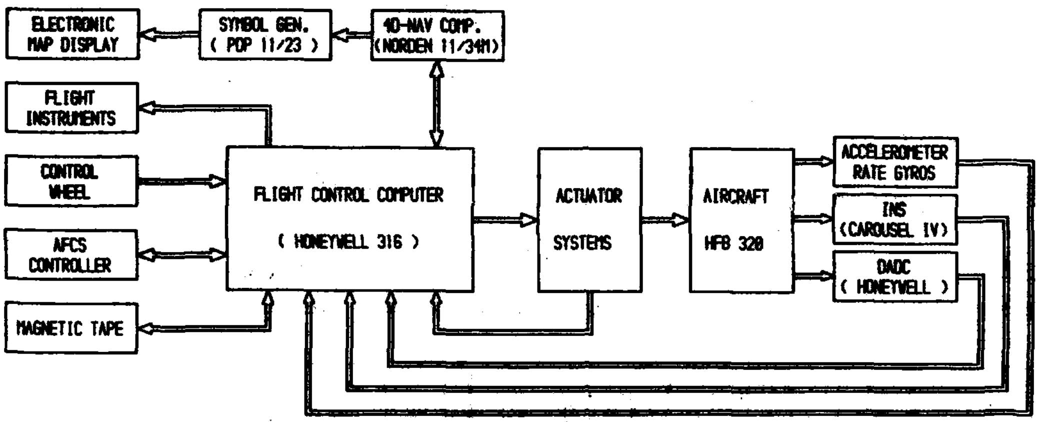


Figure 10: Structure of the digital flight control system

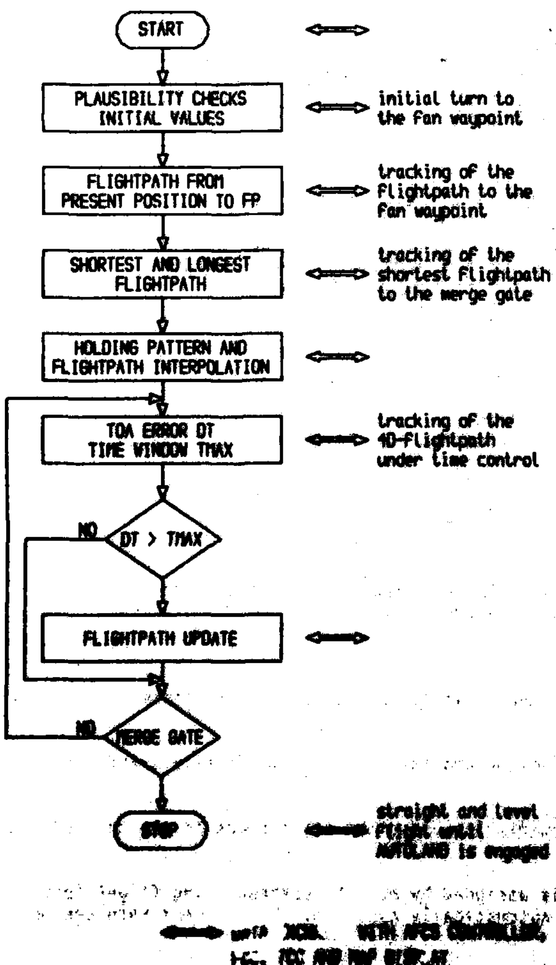


Figure 11: Algorithm sequence and aircraft actions

An integrated digital flight control system (Fig. 10) implemented in the HFB 320 test aircraft of the DFVLR is used for the 4D guidance experiments. It was developed by the DFVLR, at times in cooperation with the companies MBB, VFW and BGT [15, 16, 17].

This system has got a hierarchical structure for the flight control modes corresponding to the level of automation. The basic control modes are the control wheel steering modes by which the pilot can intervene the automatic system at any time. By operating the control wheel he can command changes in vertical speed and bank angle, respectively. The autopilot/autothrottle control modes are activated by pressing buttons on the AFCS controller panel. Also guidance commands are keyed in on this panel. Automatic control modes for longer flight phases, such as the 4D mode, work on the autopilot/autothrottle control modes. The flight control algorithms correspond to a coupled multivariable control system with open loop and feedback control. The controls are rudder, ailerons, elevator and throttle.

The software of the flight control computer (HONEYWELL 316) is modular in structure. Each control mode corresponds to a software module.

4.2 4D NAV Software and CPU times

The entire software which has been developed for the 4D NAV mode is stored in a separate computer (Norden 11/34 M). It is written in FORTRAN and modular in structure, too. This facilitates the testing of the software and the optimization with regard to minimum CPU time.

Figure 11 shows the principal flow diagram for flightpath precalculation, time control and flightpath update. The total planning computation is partitioned so that a very fast response on pilot inputs is guaranteed. That means the pilot can immediately observe a corresponding reaction when he makes any input on the AFCS controller panel.

Typical CPU times as required in a Norden 11/34 M computer for the different calculation steps are listed in Figure 12.

A		flightpath pre-calculation		3.5 s
	A1 :	initial turn to the FP	0.04 s	
	A2 :	flightpath to the FP	0.06 s	
	A3 :	horizontal flightpath	1.00 s	
	A4 :	holding pattern	0.50 s	
B	:	TOA error computation		0.3 s
C	:	flightpath update		3.0 s

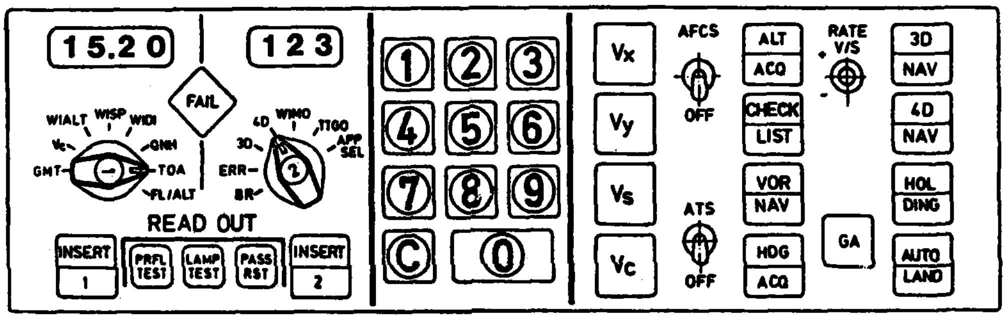
Figure 12: CPU times for different calculation steps

In particular three values of CPU time are important, namely those for:
- the pre-calculation of the complete 4D flightpath (part A),
- the continuous calculation of the TOA error (part B) and
- the determination of a corrected flightpath (part C).

A total of 3.5 seconds are required for part A. If no holding is necessary, only 3.0 seconds in total are sufficient to determine the complete 4D flightpath.

4.3 Operation of the 4D mode

The pilot inputs are made on the data entry panel of the AFCS controller shown in Fig. 13.



GMT	:	actual time in absolute numbers	FL/ALT	:	commanded flight level
VC	:	commanded airspeed	ERR	:	error code
WIALT	:	altitude of the reference wind	4D	:	code number of the approach route
WISP	:	magnitude of the reference wind	WIMO	:	code number of the wind model
WIDI	:	direction of the reference wind	TTGO	:	time-to-go in minutes
TOA	:	desired TOA at the gate in absolute numbers			

Figure 13: Front panel of the AFCS controller

The actual procedure for a typical test flight is as follows:

1. Before take off the code number of the wind model used during the test flight has to be keyed in. The following code numbers are available:
   1: wind model corresponding to Eqs. (11) and (12)
   2: wind model corresponding to Eq. (13)
   3: wind model 1 including wind prediction (Eq. (14)
   4: wind model 2 including wind prediction (Eq. (14)

2. The pilot keys in the altitude and speed assigned by ATC. These commands are fed into the automatic flight control modes altitude aquire (ALT ACQ) and speed control (VC).

3. The reference wind data are fed in.

4. The code number of the approach route to the gate and the altitude and speed for the intermediate approach are keyed in.

5. The 4D mode will be initiated by pressing the 4D NAV button and the aircraft immediately starts the approach by tracking the shortest 3D flightpath.

6. The time-to-go corresponding to the minimum TOA is now displayed and the pilot feeds in the desired TOA with the left selector switch on position TOA.

7. If an altitude change for the intermediate approach is assigned by ATC the corresponding flight level has to be keyed in. A descent rate of 1000 ft/min is automatically assigned. This descent rate can be changed by means of the RATE V/S toggle switch.

In addition to the conventional instrumentation on the instrument panel and the AFCS controller panel the experimental system is equipped with an electronic map display shown in Fig. 14.

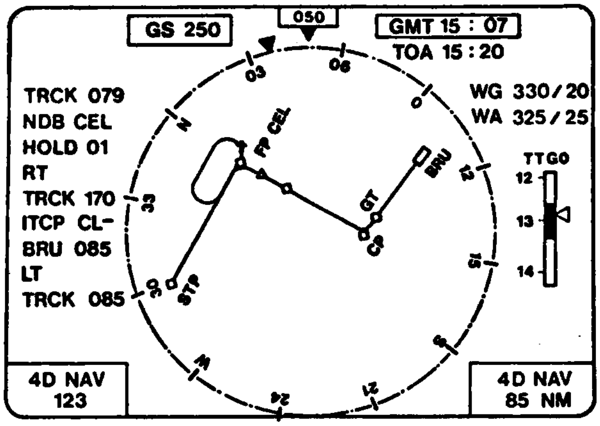


Figure 14: View of the electronic map display

The following parameters are displayed
- code number of the approach route to the gate
- mode of the flight control computer
- track angle
- heading
- ground speed
- actual wind data
- TOA error and its switching function
- absolute and relative times
- important waypoints
- symbols for the actual aircraft position
- number of holding
- symbols for descent and speed reduction
- description of the pre-calculated flightpath for manual flying
- a list of the data keyed in by the pilot can be displayed on request.

All signals required for flightpath control are provided by the onboard sensor system in a suitable filtered form. The amount of signals as well as their quality meets the standard of modern transport aircraft. The essential signals are provided by a digital air data computer (HONEYWELL DADC), an inertial navigation system (CAROUSEL IVa INS) and rate gyros and accelerometers mounted in the body-fixed coordinate frame. For the flight tests the area navigation capability is established by the unaided CAROUSEL IV INS. The position errors are limited by means of a careful alignment phase and relative short mission time of approx. 30 minutes. The CAROUSEL IV position error is about 200 m at the merge gate. This corresponds to a TOA error of about 2 seconds. This sufficiently complies with the accuracy requirement in TOA control of less than $\pm$ 5 seconds. With regard to the area navigation systems for operational use in 4D guidance it becomes apparent, that no higher precision level is necessary in position determination.

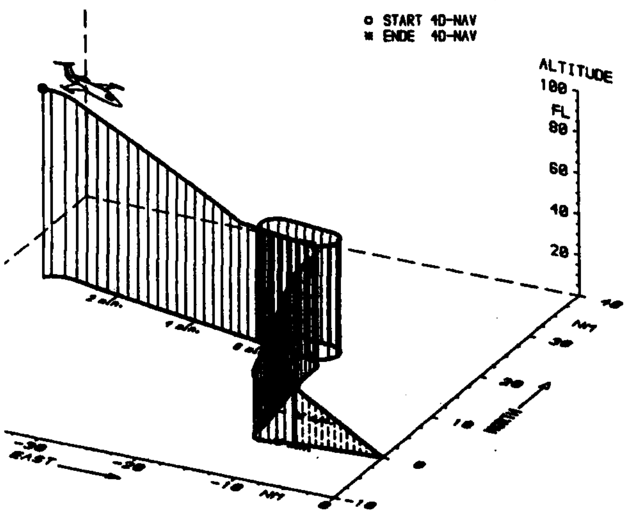


Figure 15: 3D flight path of flight test 12/2

5. FLIGHT TEST RESULTS

First flight tests of the 4D NAV mode took place in the Hannover and Braunschweig area in summer 1982. A large number of flight tests are planned in order to investigate various TOAs, speed and altitude profiles and wind models in varying weather conditions.

The flight test selected for this presentation took place on May 25th, 1982. On this day an interesting wind profile was observed with a minimum magnitude of approx. 10 kts at FL 60 and a value of 20 kts at FL 100 and FL 30. The 3D flight path is shown in Fig. 15.

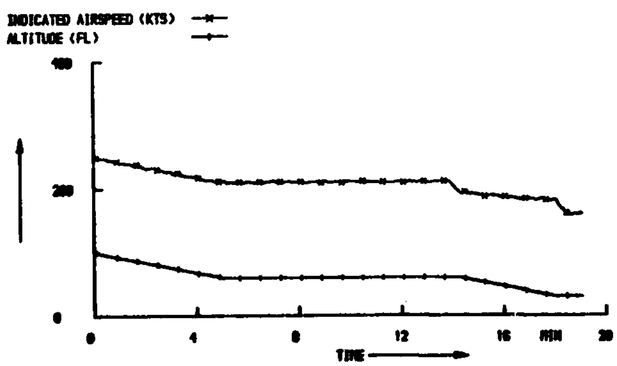


Figure 16: Speed and altitude profiles of flight test 12/2

The 4D approach was started approx. 45 nm off the gate. The fan waypoint is located at a NDB radio station. Flightpath command updates are performed by means of small course changes during intermediate approach. The desired TOA at the merge gate keyed in on the AFCS controller panel by the pilot was too late to enter the fan directly, i.e. a holding had to be flown that was planned to take exactly 5 minutes flight-time.

Fig. 16 shows the airspeed and altitude profiles associated to this approach. The descent took place in two steps and the speed was reduced corresponding to the previously defined deceleration rates of 1 kts/s for level flight and of 0.2 kts/s during descent.

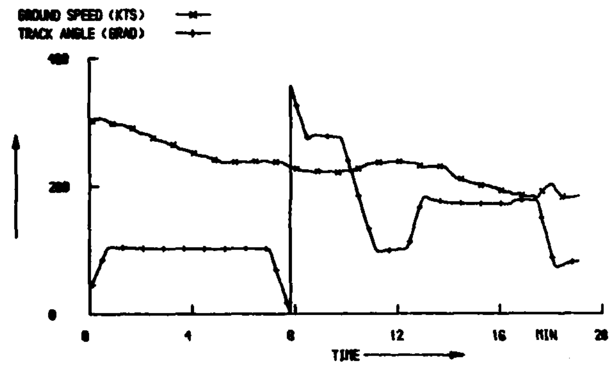


Figure 17: Ground speed and course angle of flight test 12/2

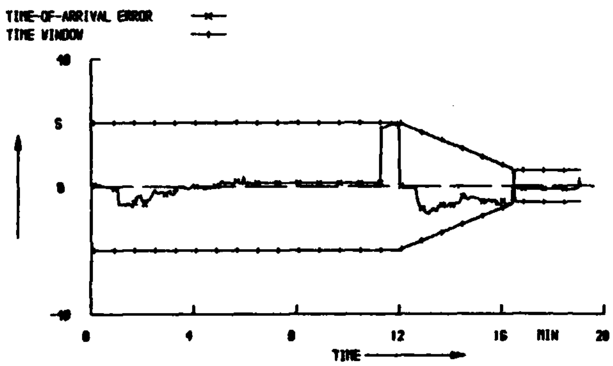


Figure 18: TOA error and time window for flight test 12/2

In Fig. 17 the ground speed and the course angle are plotted. The ground speed reflects the commanded steps of speed reduction and, depending on the value of the course angle and flight altitude, illustrates the influence of the wind, acting on the aircraft from various directions for example while the holding is performed.

The TOA error for the selected 4D approach is shown in Fig. 18. The holding was executed at FL 60, at which a deviation of approx. 10 kts was observed between the wind model and the actual wind profile. This led to a relative TOA error of about 20 seconds when the holding procedure was finished. At the fan waypoint an update computation took place taking into account the corrected wind profile. The last update compensates for a relative TOA error of approx. 5 seconds. By the time the gate was reached the TOA error was reduced down to about -1 second.

6. CONCLUSIONS

For the best use of airport approach capacity the 4D guidance system is an essential and promising element of TMA flight guidance automation. The system presented in this paper was developed for use during TMA flight from the metering fix to the merge gate located on the extended runway centerline about 12 nm off the runway threshold. At this point the aircraft is supposed to have assumed a given state in speed and altitude at a given time. First flight test results have shown that the TOA error at the gate meets an accuracy requirement of 5 seconds.

Flightpath stretching or shortening via a delay fan is applied almost exclusively for time control and indicated airspeed is used for speed commands as conventional. This allows for manual flying of the commanded 4D flightpath and to maintain a fuel-saving state of the aircraft as long as possible. The speed and altitude profiles are composed of a sequence of constant values corresponding to the usual radar vector guidance commands. The altitude is assigned by ATC. Different wind models are beeing investigated, in order to find the one best suited for the actual wind profiles. The accuracy level achievable in 4D systems above all depend on the precise knowledge of the wind profile along the pre-calculated flightpath.

Iterative and fast-converging algorithms were developed for the calculation of the flightpath, TOA error computation, path correction calculations and holding computations. The hard- and software components were tested on the ground by means of the precise simulation of the HFB 320 test aircraft.

First test flights were started in May, 1982 and a typical 4D approach from this test series is shown in order to illustrate the principle features and the performance of the 4D System.

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This volume contains papers presented at the Special Session on Air Traffic Control in face of Users' Demand and Economy Constraints sponsored by the Guidance and Control Panel of AGARD upon the request of the Portuguese Authorities.

Two overview papers and 10 papers were presented under the following headings:

- Present situation and requirements (Overview)
  - Present and Future Trends
  - The Views of the Users
  - Air Traffic Situation in Portugal
- Potential Developments and Applications (Overview)
  - Overview of Technological Developments
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